Team AeroPac's 2012 100k' Rocket Program

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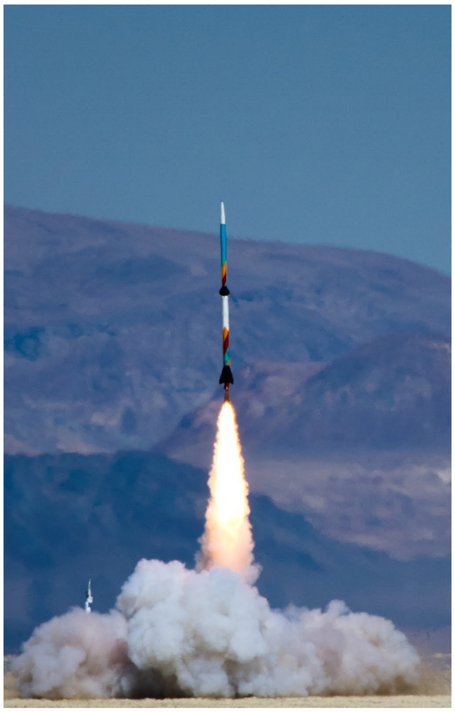

Photo: Ken Adams

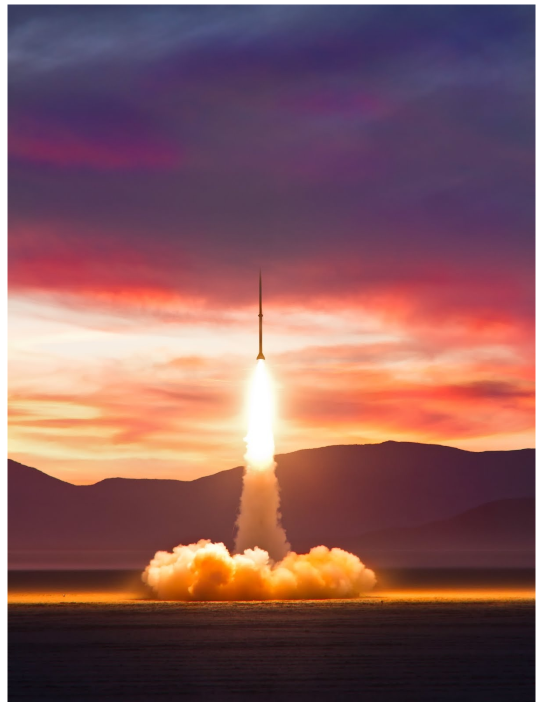

Photo: Tom Rouse

The view southwest of Black Rock from 104k' AGL

Executive Summary

The dream of space has tantalized many men and women. Today, we can reach space–but it is largely a project left to governments, rather than amateurs and hobbyists. Advances in technology, materials, and electronics now make the dream of space increasingly accessible, not just to governments and corporations, but also to talented teams of hobbyists.

On September 11, 2012, a team of experienced hobbyists reached a milestone on the journey toward amateur space flight: A GPS-documented flight to 104k' above ground level, with full recovery, using only 21,000 N*s of propellant. This report reviews that project.

1.0 Program Goals

The **100k** project is the culmination of a five year ambition for many of the team members to design and build a rocket to reach and exceed the altitude of 100,000 feet Above Ground Level (AGL).

The goals of the project were:

- Complete a rocket flight to near-space with apogee of 100k'+ AGL under terms compatible with winning the Carmack Prize[1]. As of the date of this report we understand we have satisfied those terms.
- Use an airframe design philosophy of low drag and high efficiency to maximize use of propellant energy to get as high as possible on as little propellant as possible.
- Create an airframe based on commonly available materials and commercial motors to minimize cost and maximize ease of construction both for the team and for other teams that would choose to use all or part of the design.
- Create a reusable flight profile that permits flight, recovery, and recycling of the same airframe.
- Create an airframe that is capable of carrying a usable science payload, nominally a classic CanSat in volume, with a mass of up to about 0.7 kg. We simplified our goal and did not plan for independent CanSat deployment, instead keeping the payload inside the airframe during recovery.
- Live webcast the launches to share the experience with the worldwide rocketry community–both audio/video and live telemetry from GPS and the science payload.
- Document the project in a manner that the airframe (and hopefully, the results) can be replicated.

After an inspiring brainstorm at a club holiday party in December, 2011, we assembled an experienced team consisting of eight members of Tripoli's[2] AeroPac[3] Prefecture–the educational non-profit rocketry organization with the longest experience at Black Rock. The team also has strong ties to AeroPac's sibling organization, the National Association of Rocketry's[4] LUNAR[5] section. Collectively, the team's members have flown hundreds of M+ impulse flights, hold amateur rocket altitude records, are all Tripoli Level-3 certified (including three Tripoli TAPs), and possess the skill sets of project management, computer science, a dabbling of electronics, rocket motor construction, advanced composite construction, machining, and wireless communications (three are licensed radio amateurs, two with day jobs in wireless communications).

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[1] http://www.armadilloaerospace.com/n.x/Armadillo/Home/News?news_id=376
[2] http://www.tripoli.org
[3] http://www.aeropac.org
[4] http://www.nar.org
[5] http://www.lunar.org

2.0 Background

Our approach to the project was informed by our experience. While we all had substantial individual rocketry experience, there were three key group projects which provided the experience that informed many of our goals and our approach.

Many of our team members worked on two previous attempts to reach 100k'. The **to100k** team consisted of AeroPac members, and the **99k** team was made up of LUNAR members. These two projects had a lot in common: As both used multi-stage rockets, the participants learned a great deal about what would work and what would not. And while neither project reached the 100k' goal, both came tantalizingly close. The experiences left the participants craving success, and the lessons learned were vital in choosing our approach to this project.

ARLISS[6] (A Rocket Launch for International Student Satellites) was founded in 1999 by AeroPac and Prof. Bob Twiggs (then at Stanford University, creator of the CanSat idea and co-creator of CubeSats) to create a realistic project environment in which (generally) university-level students could create advanced robotic satellites and fly them in competition. Students from around the world create 1-kg, CubeSat sized payloads[7] that are autonomous self-guided robots. They have to survive the challenge of 8-G launch and 20-G deployment accelerations at 12,000' above the Black Rock playa and find their own way back to a target location by flying, crawling, or gliding. Or, as one project tried this year, hopping. AeroPac members build the airframes for deploying these student payloads and, in partnership with the student teams, fly the missions. Over the 14 years of the project, ARLISS has flown about 500 of these missions on M1419 motors, with only one failure to deploy a student project in that time–a 99.8% deployment success metric. AeroPac members (all experienced L3 fliers) participating in this program often fly two or three such missions a day, setting themselves a standard of reliable and consistent deployment with fast turnaround of airframes for another mission. The ARLISS program is growing; more than 1200 young engineers have participated from tens of countries. For ARLISS 2012, we had 49 missions flown by 25 teams from 6 countries. We expect that number to increase in 2013. 75% of our team members are ARLISS fliers.

While many of our team members are experimental rocket motor builders, our goal was to use commercial motors to increase the accessibility of near-space to hobbyists and students who are not interested in custom rocket motor construction. The commercial motor constraint, as well as the desire for an efficient design, led us to a multi-stage airframe design.

In hobby rocketry, it's common to encounter airframes that are too large, too long, and too heavy, and thus require much bigger motors to get to altitude. Bigger motors require bigger airframes and inspire anything but a virtuous design cycle. Our goal (and bias) was to return to

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[6] http://www.arliss.org

[7] http://www.youtube.com/watch?v=PRzQpvvDU0c

the great history of small sounding rockets (ARCAS, Loki, SuperLoki, Astrobee D) and create the smallest, lightest airframe to accomplish the mission. This matched our experience in high altitude record flights, in which the least airframe to accommodate the necessary propellant was the best choice.

Our initial conception of the mission included developing a common airframe design, of which three instances would be built and flown by three separate teams: AeroPac, a new hobby team and a university team. As the project evolved, the other two teams did not effectively materialize and the AeroPac team ended up building two complete airframes (‘A’ and ‘B’) and flying these a total of five times during the test and mission flight regime. Airframe A flew four times: both test flights and the first two mission attempts. Airframe B flew the third mission attempt.

2.1 System Design

Initial simulation design studies strongly suggested we could get a two stage (4”-to-3”) airframe with about 20,000 N*s of total impulse to above 100k’. The real question was: Is this a fantasy of simulation, since no previous attempts at high altitude had used so little impulse?

We began by looking at some history. In the table below is a brief summary of the altitude and total impulse of both a classic sounding rocket–Atlantic Research’s ARCAS[8]–and some classic recent amateur high altitude flights–Ky Michaelson’s GoFast, Jim Jarvis’s FourCarbYen[9], and Derek Deville’s Qu8k[10]. The table also suggests a figure of merit, the ratio of altitude to total impulse, quantifying design efficiency.

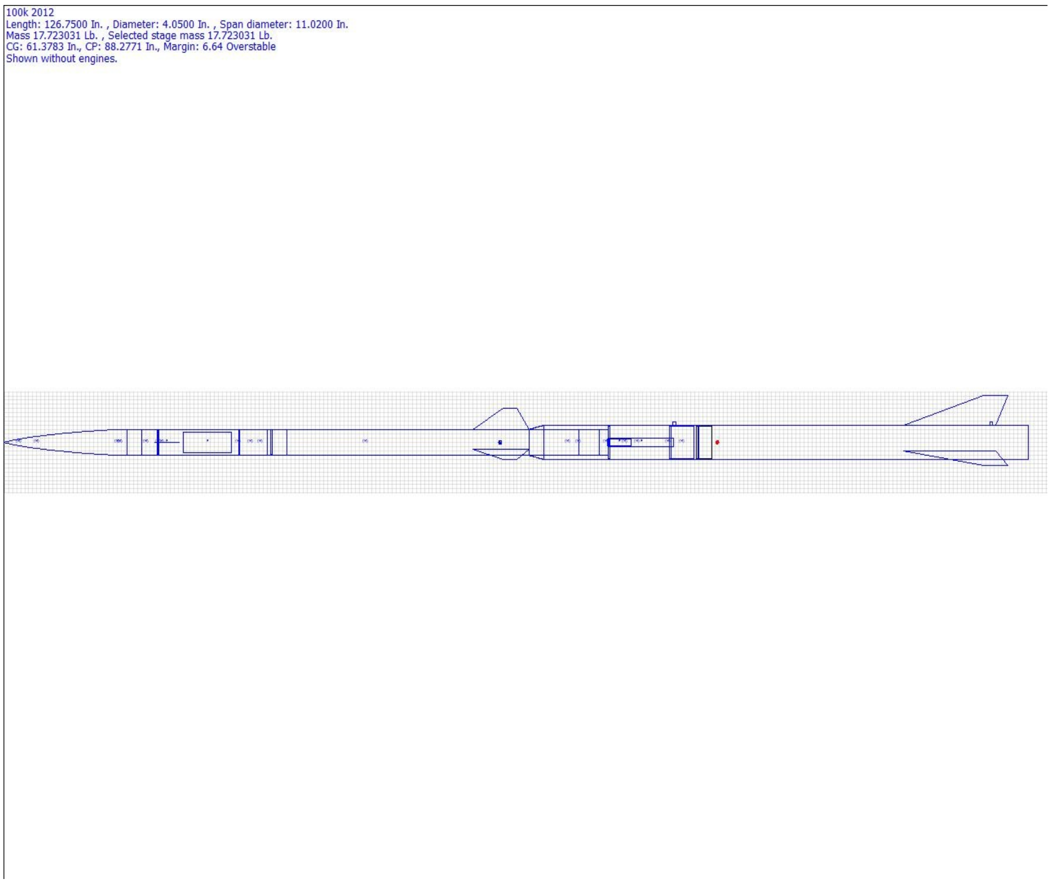
Project	Altitude (m)	Total Impulse (N*s)	Ratio
ARCAS	60960	40000	1.5
GoFast	116000	480000	0.2
FourCarbYen	32004	34150	0.9
Qu8k	36880	143000	0.3

Both GoFast and Qu8k are large, aluminum, single-stage airframes with custom motors, and both are Class-III airframes. Both are relatively inefficient on this metric as compared to ARCAS. Jim Jarvis’s FourCarbYen, on the other hand, begins to approach the efficiency of the ARCAS, and yet it is a Class-II airframe with composite construction. In our analysis, in the low-Mach-number regime, a design of a 4-inch booster staging to a 3-inch sustainer with a shorter, lighter airframe and a better nose cone showed a substantial decrease in drag over Jim’s design. We hoped this improvement would translate into an increase in altitude, even with

[8] http://www.designation-systems.net/dusrm/n-6.html
[9] http://www.rocketryplanet.com/index.php?option=com_content&task=view&id=3640&Itemid=38
[10] http://ddeville.com/derek/Qu8k.html

less propellant.

These design precedents aligned well with team members’ experience in building altitude rockets in the M-through-P motor classes, so our baseline became a Class II, 4”-to-3”, two-stage, all composite design.



Simulation Design: Ken Biba

For fin-guided rockets in the atmosphere, the best altitude performance comes with a motor that has enough initial impulse to get the airframe off the pad, but then regresses into a long sustained lower impulse burn. Such motors, in the same airframe, will outperform motors with greater total impulse but shorter burn times because they expend less energy overcoming atmospheric drag. Many hobby rocketry projects, particularly staged projects, use very high impulse motors with short burn times. We decided to take advantage of the physics of drag (and violate hobby rocketry conventional wisdom) by choosing to stage one long-burn motor to a second long-burn motor.

Our team had experience with both a variety of moonburning motors from various manufacturers and found that Aerotech’s N1000 had, incrementally, the best overall performance. We chose this as our baseline booster motor. Our initial choice for the sustainer motor was the Cesaroni M840, but Aerotech delivered the M685 just in time for our first flight, with incrementally longer burn time and a smidgen more total impulse. We retained the CTI M840 as our backup sustainer motor.

2.2 Simulation

The next challenge was benchmarking the performance envelope of this system. We turned to simulation tools.

The team was most experienced with RocSim Pro[11] from Apogee. However, we knew from experience in high altitude flights that its drag calculation algorithm, particularly for supersonic flights, substantially overestimated drag and hence underestimated altitude. But we liked and trusted RS Pro's 6-DOF basic flight modeling, wind modeling, and Monte Carlo simulation methodology for estimating flight dispersion patterns. RS Pro also has a method for inputting a Coefficient of drag (Cd) curve determined externally, overriding the pessimistic internally generated one. But where could we get good Cd information to feed the simulation?

We had hoped that a university team would be participating in the project and would take on the research effort of using industry-standard tools to determine the drag profile. Unfortunately, that did not materialize. So instead, we began a survey of amateur-class modeling tools that would give a good estimate of drag. We had the advantage of several high altitude projects with real performance data on which to benchmark and calibrate these tools.

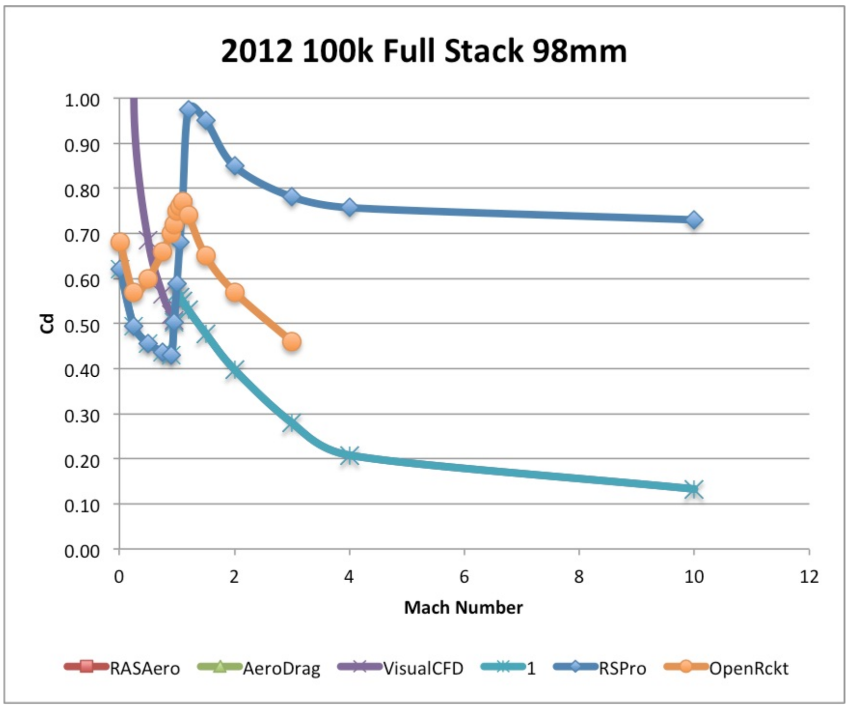
We also surveyed AERODrag[12], OpenRocket[13], RASAero[14], RockSim[15], and VisualCFD[16]. We discovered the following:

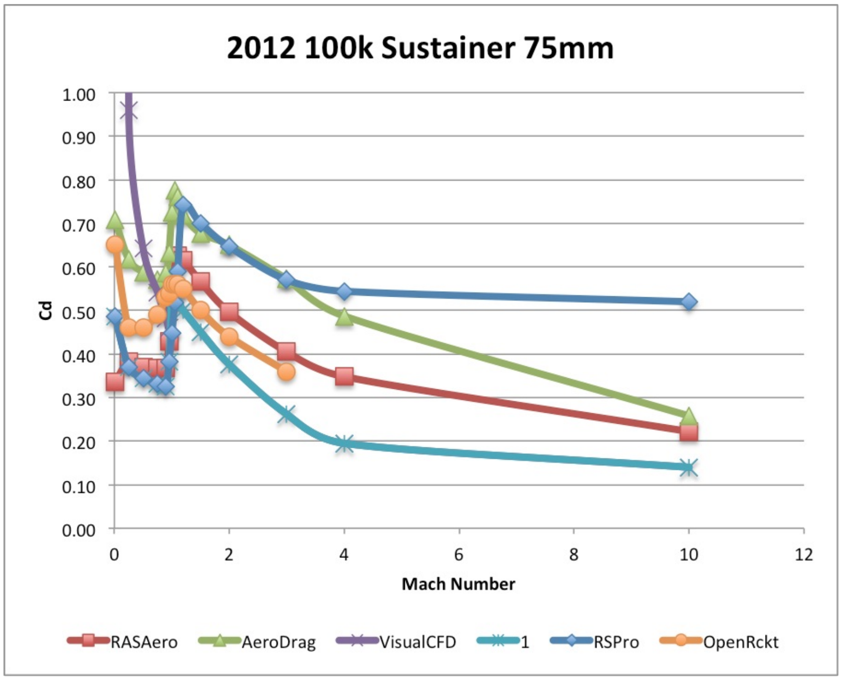
Tool	Comments
AERODrag	Drag estimates seem materially too high.
OpenRocket	Drag estimates not bad. Simulation estimates not bad. As one integrated tool for multistage design and simulation may be the best all around choice. A bit awkward to use and inadequate Monte Carlo dispersion analysis for high altitude flight.
RASAero	Limited to single-stage. Single-stage Cd estimates appear quite good. However, the simulation engine seems overly optimistic, materially overestimating altitude. No dispersion analysis. Not really a design tool.
RockSim	Decent design tool. Pessimistic Cd estimates, particularly supersonic.

11 http://www.apogeerockets.com/Rocket_Software/RockSim_Pro/RockSim_Pro_v1_CD
12 http://www.aerorocket.com/aerodrag.html
13 http://openrocket.sourceforge.net
14 http://www.rasaero.com
15 http://www.apogeerockets.com/Rocksim/Rocksim_information
16 http://www.aerorocket.com/VisualCFD/Instructions.html

	No dispersion analysis.
RockSim Pro	Decent design tool. Decent 6-DOF simulation engine. Pessimistic Cd estimates (essentially the same as RockSim). Pretty good dispersion modeling yielding Google Earth dispersion patterns.
VisualCFD	A "desktop" computational fluid dynamics tool. A marginal UI, highly labor intensive, but compared to industrial-grade CFD programs, surprisingly computationally efficient. Its predictions closely match our experience. Not really a design or simulation tool.

The results for our airframe can be compared in the following Cd-vs.-Mach number graphs for both the full stack and the sustainer alone.



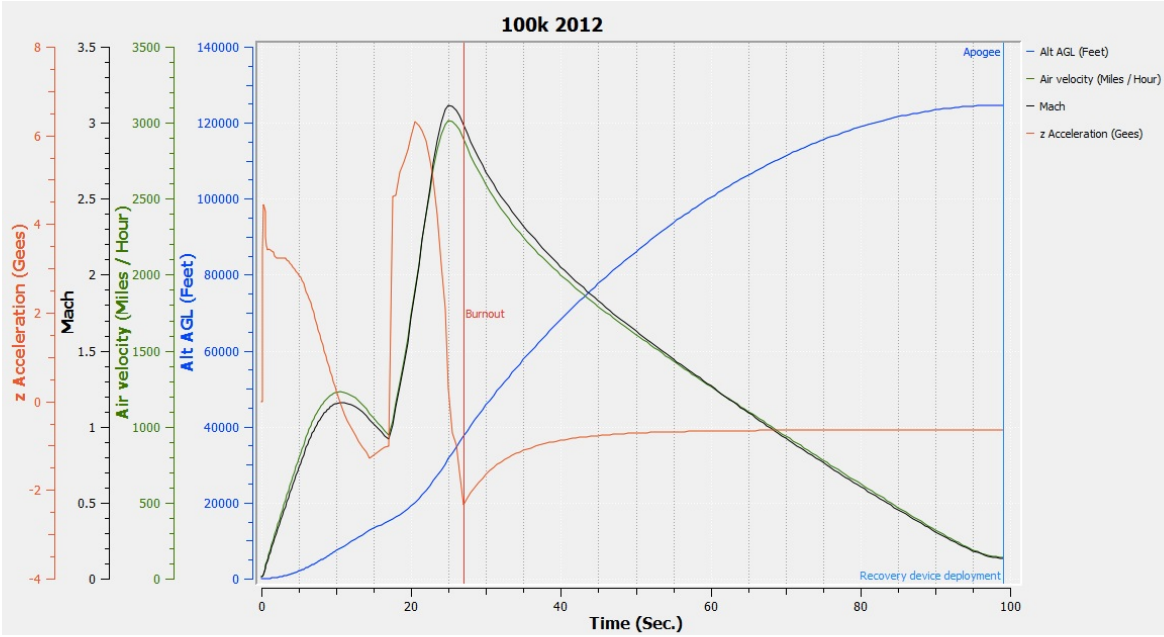


Simulations: Ken Biba

We ended up creating a composite Cd curve (labeled “1” in above graphs), largely using RASAero’s estimate for the subsonic regime and VisualCFD’s estimate for the supersonic regime. We like the agreement between model and reality using this estimate. As the graph makes clear, most hobby rocket tools substantially overestimated drag, particularly supersonic drag.

One of our team members has been studying high altitude winds at Black Rock for some time, and the data he compiled from historic NOAA radiosonde data fed our wind model for the Monte Carlo dispersion simulation.

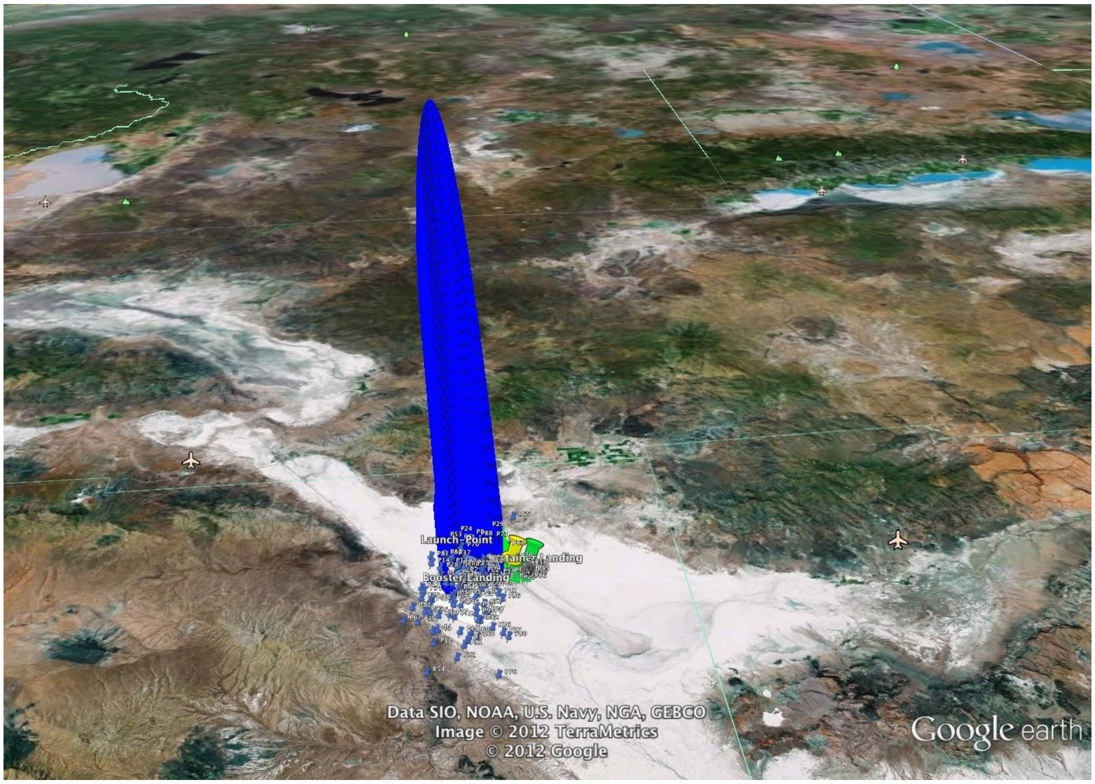
We then ran a number of simulations of proposed flight plans and airframe designs using RockSim Pro, given these Cd-vs.-Mach number curves, wind models, and motor choices. This gave us estimates of system performance, both in altitude and in flight dispersion.



N.B., the velocity curve in the simulation graph is mislabeled; the velocity is in fps.
Simulation: Ken Biba

These simulations gave us confidence that the performance envelope for this system was about 120-130k' AGL at Black Rock. Maximum acceleration was consistently under 10 G and maximum velocity in the lower atmosphere was quite low, thus minimizing lost energy to drag and minimizing the need for special heat resistant materials.

Our wind model and simulation gave us the tools to create a dispersion pattern for the booster and sustainer based on a 100-iteration Monte Carlo simulation, varying the wind patterns around the RMS variation in wind velocity and direction sampled over a multiyear, multiday radiosonde sample.



Monte Carlo Simulation of Nominal Flight: Ken Biba

These Monte Carlo simulations gave us confidence that with a straight, nominal flight, in the winds we could expect in September at Black Rock, we would recover well within waiver, and likely recover on the playa within 3 miles of the launch point.

2.3 Waiver

Our flight simulations suggested a wide range of possibilities for altitude, all dependent on what the Cd of the airframe really was. Internal guesses from the team ranged from just above 100k' to over 140k' AGL, with simulation results between 120-130k' AGL. So we needed a waiver greater than the normal 100k' MSL waiver AeroPac was historically granted. One of our team members worked with the FAA early in 2012 to increase AeroPac's standing waiver to 200k' MSL with a 10 NM radius. Our Monte Carlo dispersion analysis suggested this was more than sufficient for flight and recovery based on our historical wind analysis and expected range of airframe performance.

With Tripoli's BALLS 2012 launch now being granted a much higher waiver in September 2012, we expect AeroPac's standard waiver for 2013 to be substantially higher, too.

2.4 Mission Plan

Our mission plan was to do a series of test flights to validate avionics, recovery, and staging. We also hoped that initial test flights would provide us experimental Cd data over a broad enough range to validate our CFD calculations.

We decided to fly two test flights–one of the sustainer alone, largely to validate recovery and avionics, and a second with a full stack to validate staging and the complete system design. Both test flights incorporated lower-impulse motors to allow for convenient recovery and tracking. As our flight analysis will discuss, both these test flights gave us important information to tune the airframe, avionics and recovery.

We ended up building two mission-capable airframes that we targeted for launch at AeroPac's XPRS/ARLISS launch in September, 2012. One great benefit of this launch is that it is a week long, letting us pick the best day(s) to fly based on weather, with some time margin for last minute problems. With the week long schedule, we could plan for multiple flights.

We planned for three flights:

1. Airframe A with an Aerotech N1000 staging to a new Aerotech M685 (longest total burn and total impulse), if the motor was available in time
2. Airframe A with an Aerotech N1000 staging to a CTI M840 (a decrease of about 1 second in total burn time and few hundred N*s in total impulse–and perhaps 5k' in maximum altitude), and
3. Airframe B with the same motor configuration as Flight 2.

We felt that, with a plan of three flights, we could work out most of the inevitable bugs in the system and have a good chance of achieving our goal.

The basic mission profile is:

- Launch off 12-14' rail.
- Force staging with piston ejection at end of booster motor burn at 14 seconds. If drag separation occurs earlier, that is just fine. Separation occurs at about Mach 1.1.
- Booster continues stable independent flight with separate two-phase recovery.
- Sustainer triggers motor ignition at 17 seconds into flight, allowing for a 3 second coast to clear booster. We expect the motor to take 1-2 seconds to come up to pressure, yielding total coast time of about 4-5 seconds at an ignition speed of about Mach 0.85. The low coast time minimizes the risk of a gravity turn.
- Sustainer boosts for 10 seconds, reaching a maximum velocity of about Mach 3 at about 35,000' AGL.
- Sustainer coasts to apogee, estimated at T+100 seconds, at about 125k' AGL. The sustainer is supersonic until about 68 seconds into the flight, but almost all the high speed (and high drag) is above 20k' AGL.
- Sustainer deploys minimal recovery at apogee with main deployment just above the playa.

3.0 Design and Construction

3.1 Material and Vendor Choices

The flight regime of this airframe is kept deliberately slow to minimize total drag. Maximum drag is experienced at the top speed of the sustainer. However, that top speed occurs at 20-35k' AGL, where the reduced air pressure imparts less total drag and less heating.

Many performance-oriented designs use carbon fiber or aluminum tubing. However, this flight profile allows us to use relatively simple composite construction based on off-the-shelf, filament-wound fiberglass tube. Since we wanted to place a number of radios in the design, the radio transparency of fiberglass allowed more flexibility in the placement of antennas for both GPS reception and telemetry downlink. The low cost of fiberglass tubing also benefitted our stated goals of minimizing cost for teams wishing to replicate our design. We chose to carbon-laminate and vacuum-bag the fin cans to make them strong enough for Mach 3 flight, and these are the only sections of the airframe that use carbon fiber.

The basic airframes and fin cans for the sustainer and booster are each built as a single, integral piece with no airframe breaks. Each is effectively a sleeve over a core, consisting of the avionics bay bolted to the motor casing forward closure. The avionics bays act as the forward motor thrust plate, leading to a strong, light, and simple design.

We sourced enough components to build three complete airframes and, in the end, built two, dubbed 'A' and 'B.'

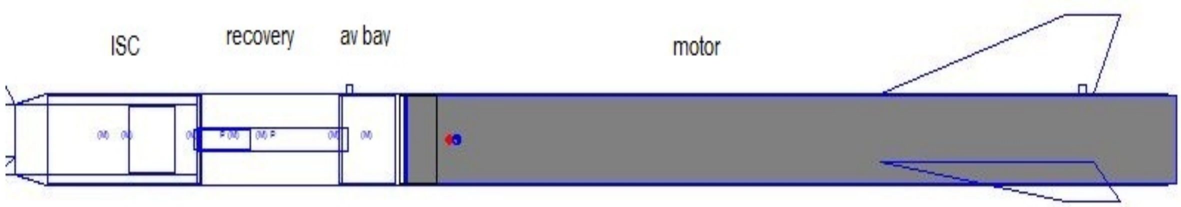
3.2 Airframe Design

As described, the basic design is a two-stage, minimum diameter rocket, with a 98-mm booster staging to a 75-mm sustainer. In order to keep weight and drag to a minimum, overall length is kept as short as possible while fitting all of the required components: motor, avionics, recovery, cameras, etc. An additional science payload is accommodated in the nose cone. This ended up resulting in just over 5 feet in length each for the booster and the sustainer, for an overall stack length of roughly 10.5 feet.

Recovery components are deployed entirely out of the forward ends of each stage to eliminate the need for any breaks or couplers within the airframes, which would introduce potential weak points. Each stage is built from a single continuous piece of tubing - which is in turn reinforced by internal avionics bays and the motor casings themselves.

The sustainer is designed such that the sustainer motor hangs out of the aft end of the airframe roughly 5 ½ inches, mating with the interstage coupler (ISC) at the forward end of the booster, so the aluminum motor case itself provides the strength for the stack.


payload
recovery
av bay
motor


ISC
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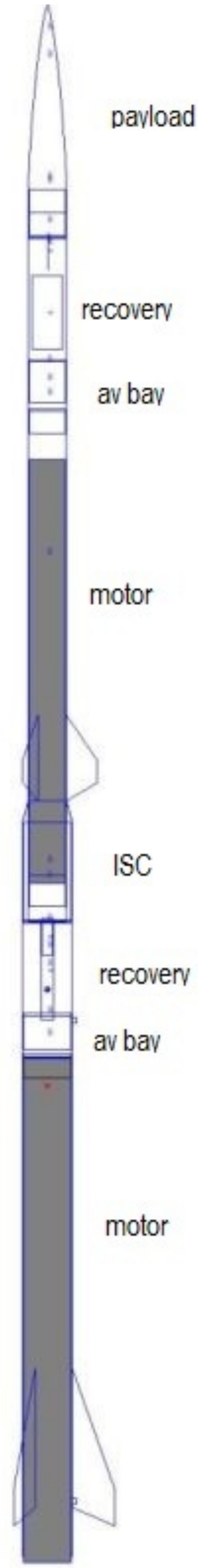

CAD Drawings: Steve Wigfield

3.3 Nose Cone

The nose cone is an off-the-shelf, 3”-diameter, 5:1 Von Karman nose cone made by Performance Rocketry[17]. It is constructed of filament-wound fiberglass with an aluminum tip. It measures 17.25 inches long, with a 3.25-inch shoulder. The 17.25-inch length includes the 2.5-inch aluminum tip. The tip unscrews, and we’ve modified the attachment slightly to allow us to easily add and remove ballast weight to give us the correct static stability for flights without a science payload.

“Von Karman” refers to the shape of the nose cone. There is a common misconception that conical nose cones are the most efficient shape for supersonic flight. This most likely comes from the limitations of hobby-level simulation software, which tend to calculate drag mainly based on surface area, and tend to severely underestimate Cd for supersonic flights.

For flights in the low-supersonic region (low Mach numbers), Sears-Hack nose cones (of which Von Karman is a special case) are more efficient[18] than conical nose cones.

The original research papers on the subject from NACA (the precursor to NASA) from the 1950s are available online:

> William E. Stoney, Jr.; NACA Research Memorandum NACA-RM-L53K17; "Transonic drag measurements of eight body-nose shapes" (February, 1954)[19]

> William E. Stoney, Jr.; NACA Research Memorandum NACA-TN-4201; “Collection of zero-lift drag data on bodies of revolution from free-flight investigations” (January, 1958)[20]

The aluminum tip is important because most of the aerodynamic heating, which might otherwise weaken the fiberglass, occurs at the very tip of the nose cone. The rest of the nose cone is in a turbulent region in the shadow of the Mach shock wave, and experiences very little aerodynamic heating.

The nose cone shoulder holds the sustainer’s GoPro camera, looking out a corresponding hole in the airframe. The camera is secured a by a bracket and all-thread to an aluminum plate at the base of the nose cone. Also mounted to the aluminum plate is the CD3 that is used for separation of the nose cone at apogee.

The remainder of the science payload is housed in the nose cone body above the GoPro camera.

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[17] http://rocketrywarehouse.com/product_info.php?products_id=359
[18] http://en.wikipedia.org/wiki/Nose_cone_design
[19] http://naca.central.cranfield.ac.uk/reports/1954/naca-rm-l53k17.pdf
[20] http://naca.central.cranfield.ac.uk/reports/1958/naca-tn-4201.pdf

The nose cone shoulder is secured to the airframe by two 2-56 nylon screws, which serve as shear pins.

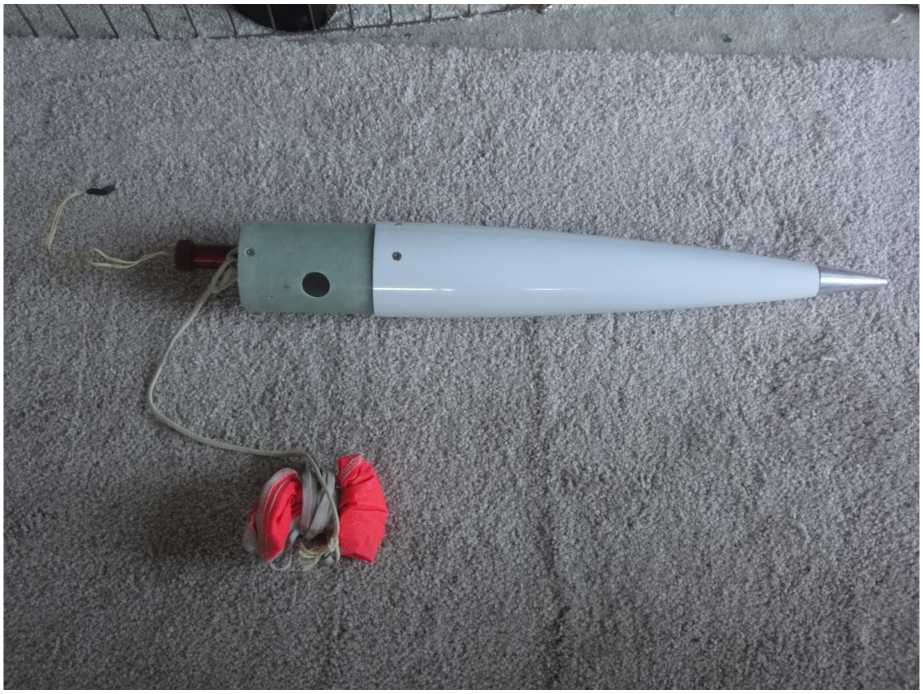


Photo: Erik Ebert

Photo: Ken Biba

3.4 Fin Construction

The airframe fins needed to be lightweight and strong. The fins were constructed and attached in a multi-step procedure designed to impart strength, as well as a strong attachment to the airframe.

Fabrication of Fiberglass/Carbon Fiber Composite Plate

We selected 0.0625”-thick G10 fiberglass plate as the fin core and sanded it with 36 grit sandpaper so epoxy could adhere properly.

We then cut CF to size, along with a layer of peel ply and breather mat for each face. We weighed the CF and mixed up about 10% more epoxy by weight to come as close as we could to our ideal ratio of 1:1 CF to epoxy. The extra epoxy allowed for what we would lose in the mixing cup and roller applicator.

We made two MDF cauls for the vacuum bag lay-up. The bottom caul was covered with plastic film. The G10 was placed on the film and epoxy applied with a roller. The CF was applied and all air bubbles were worked out with the roller. We then applied a layer of peel ply and breather cloth. We applied the top caul and plastic film to the lay-up and flipped the entire assembly over. The first caul and plastic layer were then removed, and epoxy and CF were applied to the second face of the G10. We rolled out air bubbles and applied the peel ply and breather, then replaced the plastic film and MDF caul.

Becky Green and Steve Wigfield Applying Peel Ply
Photo: Casey Barker

We inserted the entire assembly into the vacuum bag, sealed the bag, and turned on the vacuum pump. The assembly was kept under vacuum overnight. When the assembly was removed, the cauls and plastic film came off easily. The peel ply and breather, which came off together, had to be removed with pliers.

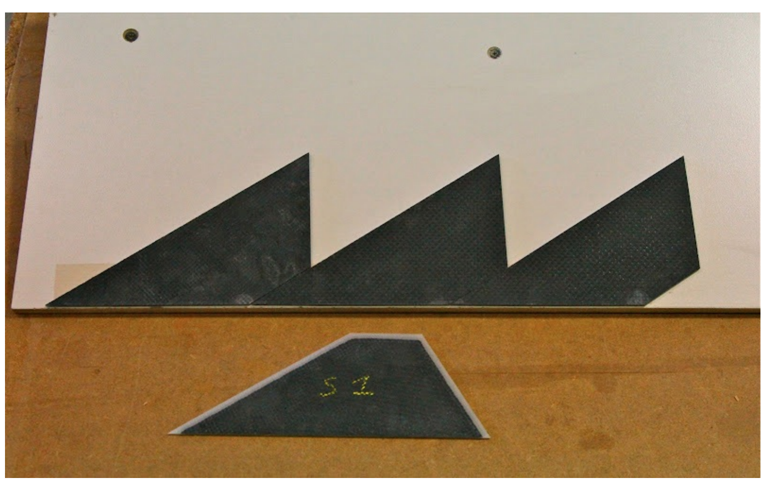
After the epoxy fully cured, we had a stiff composite plate that was about 0.85” thick.

Fin Fabrication

The next step of construction was to create individual fins. We drew the fin shapes in a CAD program and printed patterns, then traced the fin shapes onto the fiberglass/CF composite plate.

Laying Out Templates
Photo: Melanie Barker

We roughed out the shapes with diamond-wheel cutters on rotary tools, then trimmed them closer to size with a tile wet saw. They were then taped together in groups of three using the roots as a reference edge, and sanded to final size using a disk sander. The groups were labeled to keep the sets straight through the following operations.



Fins in Tapering Jig
Photo: Steve Wigfield

We used a fin tapering jig, mounted to a disk sander, to taper all of the edges except the root edges. The taper was about ¼” wide on each edge of the fins, leaving a flat edge 0.030” wide.

Body Tube Preparation

The next step was to groove the body tubes for fin attachment. Grooving the tubes helped us align the fins with the centerline of the body tube and kept the fins in alignment during the attachment process.

We made MDF equilateral triangles exactly the size of the OD of the booster and sustainer tubes, and attached MDF discs, the sizes of the ID of the tubes, to the triangles to keep the tube centered on the triangles. We then attached the triangles to the body tubes with tape.

Tube Grooving Jig
Photo: Casey Barker

We tilted the table saw blade to 45° and raised it 1/32” above the tabletop and set the saw fence so the blade bisected each edge of the triangle. Three grooves were then cut into the tube the length of the fin root edge. The width of the groove was 0.060”, close to the fin thickness. The root edge of the fins were then beveled at 45 degrees to each face, creating a 90 degree bevel that matched the shape of the groove.

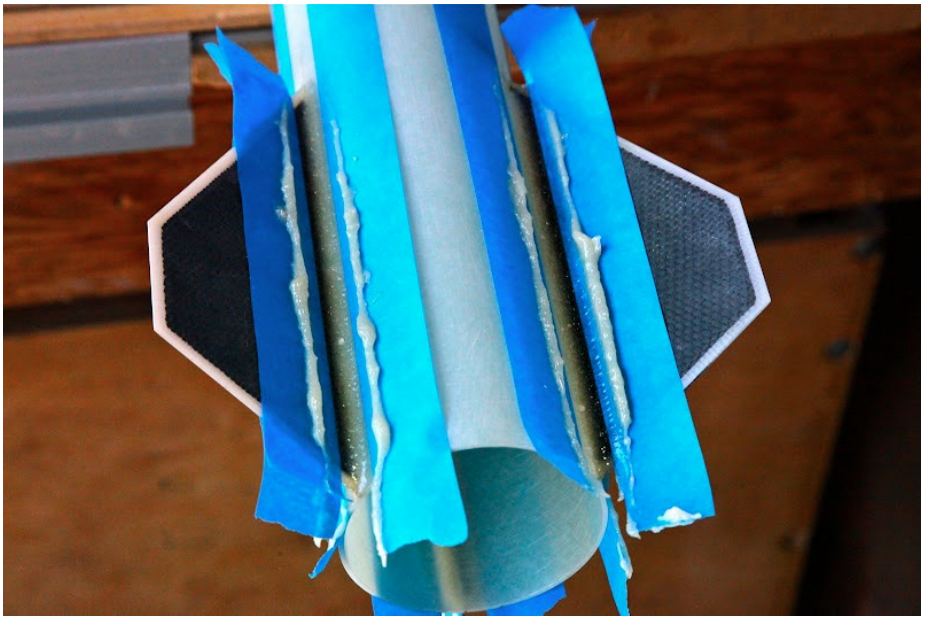
Fin Attachment

We drew a fin alignment jig in CAD, showing the body tube in plan view with the fins spaced 120° apart around the tube. The drawing was printed full size and glued to cardboard. The fin slots and the tube diameter were then carefully cut out and the tube and fins were inserted into the jig. When the fins and body tube were in alignment, we glued the fins to the body tube with super thin cyanoacrylate glue.

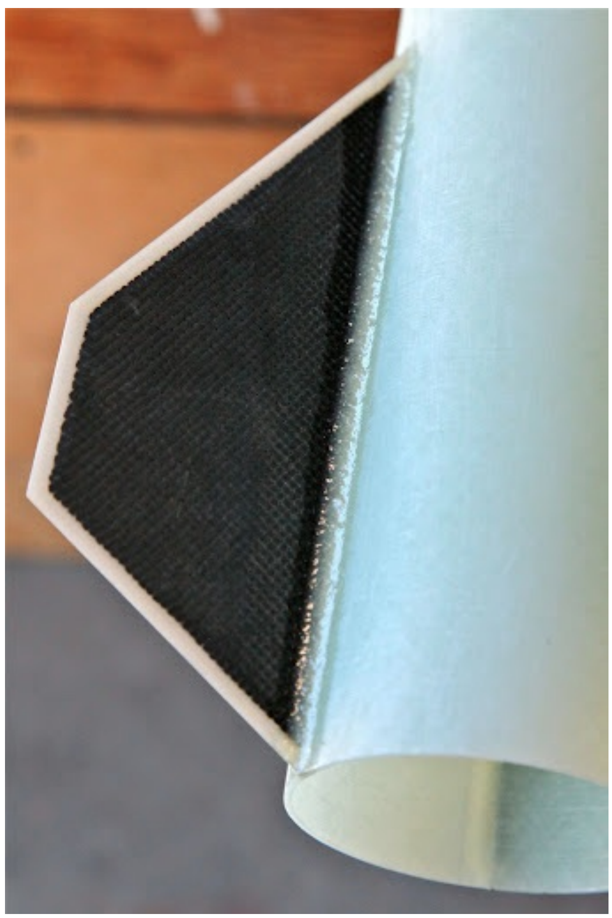
Fins in Alignment Jig
Photo: Steve Wigfield

After the CA set, the jig was removed and the tube was sanded with coarse-grit sandpaper in preparation for tip-to-tip CF application.

To create fillets, we first applied masking tape to the fins and body tube along the root edge 3/8" from the fin/body tube joint to prevent excess epoxy from getting on the fins or body tube. We placed thickened epoxy between the masking tape strips, then pulled a 3/4" diameter dowel along the joint to create a radius fillet shape. After all 6 fillets were formed, the masking tape was carefully removed and the epoxy allowed to set. When the epoxy had cured, we sanded the fillet edges flush with the fins and tube.



Fins with Fillets Setting
Photo: Steve Wigfield



Fin with Completed Fillet
Photo: Steve Wigfield

Tip-to-Tip Carbon Fiber Lay-up

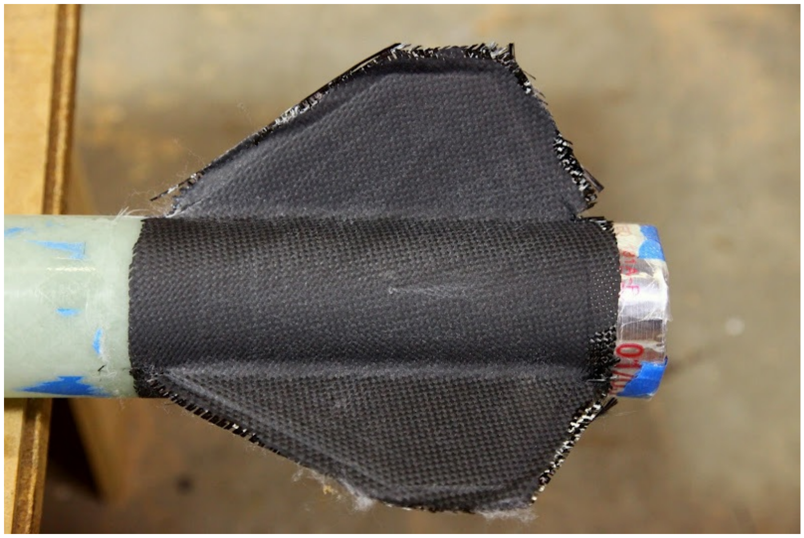
We first made paper patterns to aid in cutting three different layers of carbon fiber. The first layer covered about ⅓ of each fin, the second layer about ⅔, and the final layer covered each fin completely, tip-to-tip. The progressive layering provided several benefits: It kept the fins thin at the leading edges, varied the fin cross section thickness to reduce vibration, and strengthened the fin/body joint. This asymmetric fin planform substantially reduces the susceptibility of the fin to flutter.

We cut nine pieces of CF for each fin can, along with three pieces of peel ply and breather, in preparation for vacuum bagging the CF to the fins and body tube. The CF pieces were cut such that the weave of the first and third layers was oriented diagonally, while the second layer was oriented to the line of the airframe, creating alternating weave orientations. Six ¼”-thick MDF plates were made matching the shape of the fins.

We first set up the vacuum bag and mixed epoxy, then applied all carbon fiber layers to a fin pair before rotating the airframe and applying the next set. After all of the CF layers, peel ply, and breather were applied, we placed the airframe into the vacuum bag. We took care to form the bag around each fin, keeping wrinkles to a minimum. We used spring clamps and the MDF plates to keep the bag in place while the bag was sealed and the pump started. After the pump had pulled most of the air out of the bag, we removed the MDF plates and made sure everything had stayed in place around each fin. The airframe was left in the bag under vacuum overnight while the epoxy cured.

Bagging the Sustainer
Photo: Casey Barker

The airframe was removed from the bag and the peel ply and breather removed.

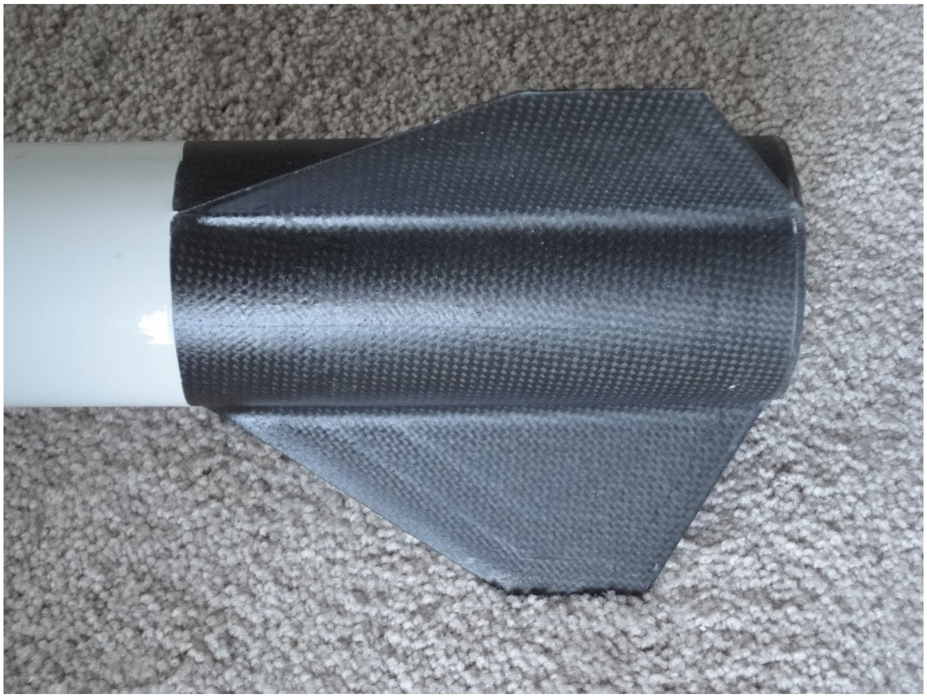


Bonded Fins before Trimming
Photo: Steve Wigfield

We then trimmed the excess CF back to the edges of the fins.

We were concerned about delamination of the CF along the leading fin edges at Mach+ speeds. To help prevent this, we applied a coat of Cotronics Duralco 4461[21] high-temperature epoxy along each leading edge. After the Cotronics cured, it was sanded fair to the fin. To finish, we applied a single finish coat of epoxy to the fin area of each airframe.

[21] http://www.cotronics.com/vo/cotr/ea_electricalresistant.htm



Photos: Erik Ebert

3.5 Interstage Coupler

Over the years, many of our team members have witnessed failures of interstage couplers during flight. The forces and strain on this part are extreme, so we took a lot of care in designing a coupler for these airframes.

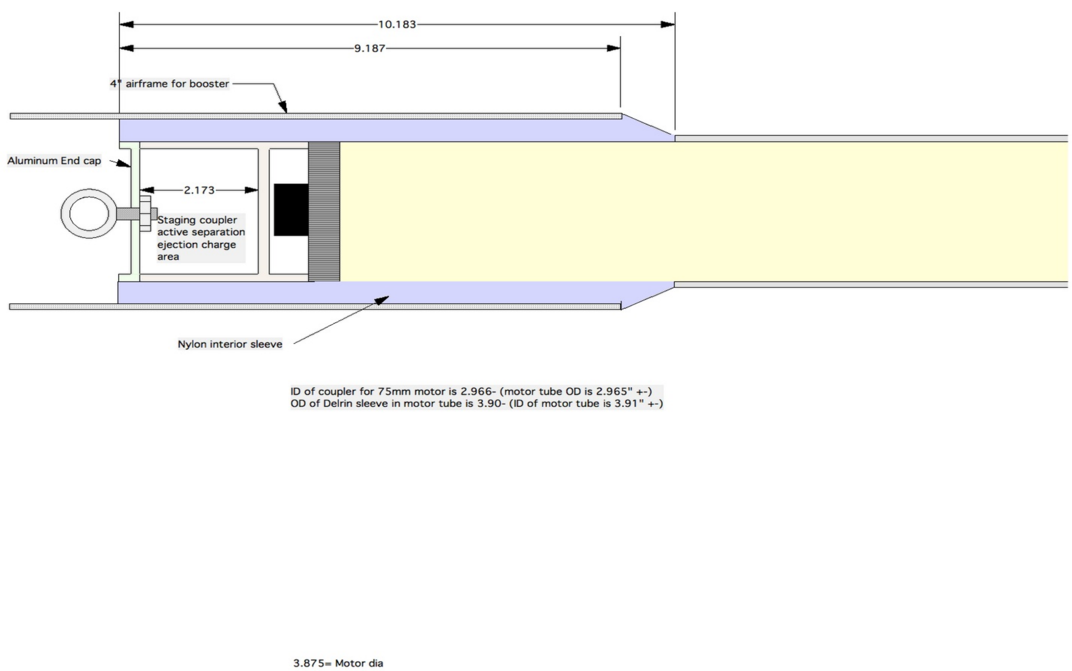
The interstage coupler (ISC) had several design constraints right from the start. We couldn't locate tubing that properly fit the 75-mm motor cases. It is unfortunate that there are no commercial 3-inch fiberglass or carbon fiber tubes with the tolerances necessary to nest the 75-mm upper stage motor inside the ISC.

The 75-mm cases have an OD of 2.965 inches and all the available tubes come in ID's of 3.002-3.005 inches. This leaves far too much slop for a rocket interstage. We decided to make our own to get the proper fit. Aluminum was our first choice, but with the machinery that we had, it was not possible to bore a solid, 10"-long piece of aluminum. Even a machine shop would need to have a large lathe to place the entire 4"-diameter piece of aluminum inside the chuck to be able to bore it properly. With aluminum, cost and weight were also concerns.

We also considered the aspect of galling. An aluminum motor tube, when mated to an aluminum ISC, stood a chance of galling and having the second stage stick inside the ISC, even though anodized aluminum supposedly would eliminate that.

We were also concerned about aluminum because the second stage received its ignition from abaft, and not from a uncertified head-end igniter. This meant that the flight computers located on top of the motor cases needed to get electricity to the nozzle end of the motor. The team planned to use two pieces of copper tape along the side of the motor case. At the rear, the igniter leads would be soldered to the copper tape. This meant that the ISC could not be conductive, or it would short out the tape circuit.

We did research to find an acceptable alternative material and decided to use Delrin acetyl plastic. It has the same coefficient of thermal expansion as aluminum, is easy to machine, and could be machined on the equipment we had. Delrin is less dense than aluminum, will not gal with the motor case, is non-conductive, and has a temperature range consistent with our flight profile. It’s also reasonably inexpensive and available in rods of sufficient size to meet our needs.



ISC CAD Drawing: Tom Rouse

Photo: Ken Biba

The ISC with Installed CD3 Canisters
Photo: Erik Ebert

3.6 Avionics

Choice of Avionics

We initially chose Featherweight Ravens[22] for the project, primarily because of their small size. To these, we added Featherweight Perches, which provided mounting, power, and a magnetic switch to the Raven. The Beeline GPS[23] tracker was chosen for both the sustainer and booster. Several of the team members reported success with the newest Beeline GPS using the u-blox 6 [24] GPS chipset. We also chose GoPro[25] cameras to provide the onboard video, placing one camera in the booster and one in the sustainer.

After the initial flight testing, we added an R-DAS Tiny[26] to the sustainer, replacing one of the Ravens, since the Ravens had shown some limitations. In the final configuration, we used one Raven, one R-DAS Tiny, and a Beeline GPS in the sustainer. The booster contained two Ravens and a Beeline GPS.

Sustainer Avionics Bay

There is very limited space in the sustainer airframe, but we had to fit the Raven, an R-DAS Tiny and a Beeline GPS unit in the av-bay. Initially, we tried to also fit a GoPro camera in the same bay, but there was no way to get all the electronics and the camera abreast inside a 3-inch airframe. The GoPro was moved to a second bay created in the shoulder of the nose cone–essentially adding the camera to the science payload. This was a better placement for the camera, and the bay also allowed a 12-gram CO_2 cartridge to fit behind the camera for apogee deployment.

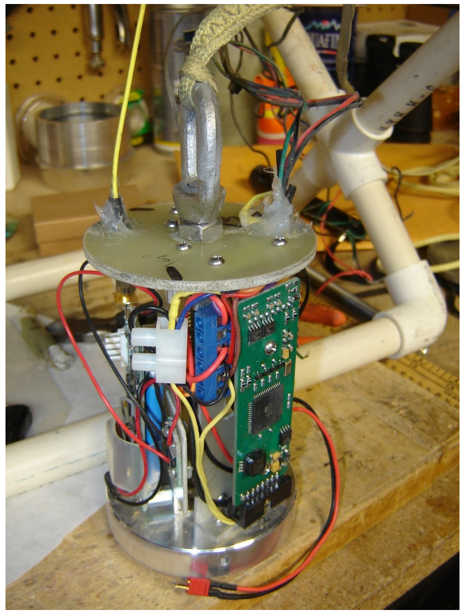
The length of the av-bay is set by the length of the Beeline GPS unit. The components are laid out in a triangular arrangement, mounted to sleds of fiberglass, allowing access to the terminal blocks on the electronics and placing the GPS antenna just inside the airframe. All the magnetic switches are positioned close to the side of the airframe. A ⅜" threaded rod passes through the center of the av-bay and is secured to the bottom end of the av-bay and motor. The rod provides a solid anchor for the recovery system, and also provides strength in the av-bay so that the electronics and sleds are not mechanically stressed.

Placement in Airframe

The av-bay is secured to the forward closure of the 75-mm 6-grain motor casing and placed in the upper airframe such that the sustainer motor hangs out the aft end of the airframe 5.5 inches. The aft end of the motor slips inside the booster's ISC and holds the booster and sustainer together with a secure fit. The aft bulkhead of the av-bay is made from aluminum and is secured

[22] http://www.featherweightaltimeters.com/The_Raven.php
[23] http://www.bigredbee.com/BeeLineGPS.htm
[24] http://www.ublox.com/en/gps-modules/pvt-modules/lea-6-family.html
[25] http://www.gopro.com
[26] http://www.aedelectronics.nl/rdas/tiny.htm

with four 8-32 screws to the airframe. The upper av-bay bulkhead was initially made from aluminum, but after the first flight, this was switched out for a fiberglass bulkhead to save weight.



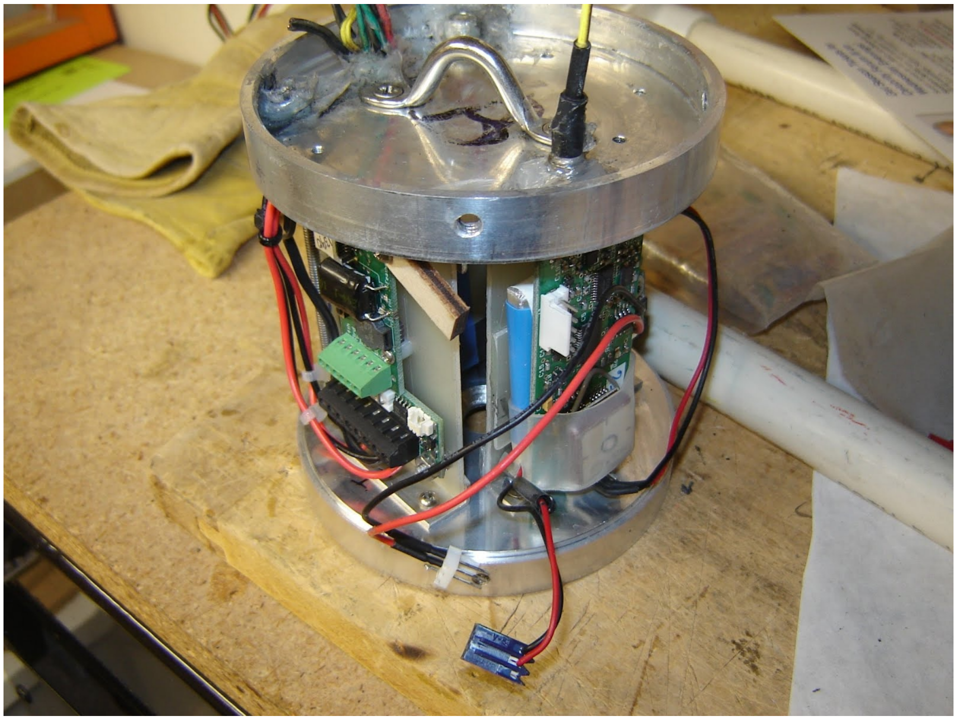
Sustainer Av-Bay, showing the Beeline GPS unit (left) and R-DAS Tiny (right). The Raven is on the far side. Photo: David Raimondi

Booster Avionics Bay

The booster av-bay fits in a 4-inch airframe and holds two Raven units, one Beeline GPS, and a GoPro camera. The layout of the electronics in the booster av-bay is in a “U” shape with the GoPro camera between the two Ravens, and the GPS facing opposite the camera’s field of view. The camera extends through the center of the av-bay, so unlike the sustainer bay, the booster bay cannot accommodate a through-bolt to secure the recovery system to the motor. Because of this, the booster bay has aluminum bulkheads at both ends. These are secured to the airframe with four 8-32 screws each. The lower bulkhead provides the forward motor retention and acts as a thrust plate. The upper bulkhead provides a solid anchor for the recovery system. Since both ends of the booster av-bay are secured to the airframe, there is no stress on the electronic components and sleds.

Placement in Airframe

The av-bay is secured to the forward closure of the 98-mm 6-grain motor casing and placed in the booster so that the aft motor closure is against the aft end of the airframe.



Booster Av-Bay, showing the Raven (left) and Beeline GPS (right). At the bottom is a tapered hole where a screw secures the N1000 motor to the av-bay. The GoPro camera faces out opposite the Beeline. Photo: David Raimondi

3.7 Recovery

Overview

The recovery system for the booster and the sustainer are designed to deploy both the drogue and main out of the forward end of the respective airframes. This eliminates the need for any breaks or couplers in the airframe tubes which would be potential weak points in the airframes. The booster and sustainer recovery harnesses are essentially identical except for size. The recovery volume is as small as possible to fit the required recovery components, in order to minimize airframe size and maximize altitude. Packing the recovery bay requires three sets of hands, considerable creativity, and a +3 Stick of Packing, in order to use every cubic inch of available recovery volume.

Recovery space is so tight that buttoning up the airframes requires two people to compress the nose cone or ISC into the respective airframe, while a third person installs shear pins. Packing the booster for a test flight proved so challenging that we went back and adjusted the design of the ISC to gain some extra recovery space in the booster (a fraction of an inch made a huge difference), but because the sustainer camera and science payload were housed in the nose cone, and because the camera's viewport was already drilled, we were unable to make a similar adjustment to the nose cone shoulder. Packing the sustainer remains challenging and requires considerable pressure.

Pyro Devices

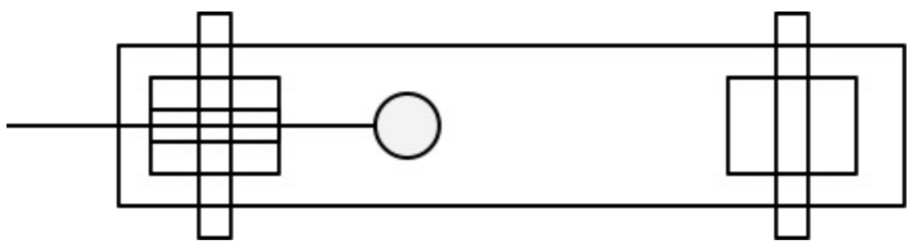
Conventional black powder pyro devices do not function well above about 20,000 feet MSL, which poses an issue even for the booster apogee (near 30,000 feet MSL). The difficulty isn't lack of oxygen, since black powder contains its own oxidizer. The difficulty seems to be heat conduction between the grains of powder. An electric match will light the nearest grains, but without air molecules to conduct heat, the combustion does not propagate to the rest of the powder. The few grains that do ignite seem to just scatter the rest of the powder without igniting it. Various members of AeroPac and others have investigated this phenomenon by testing black powder charges in vacuum chambers[27].

For maximum redundancy, two different types of pyro devices are used for high-altitude parachute deployment, RouseTech CD3s[28], and black powder sealed in surgical tubing. J-Tek e-matches are used in all pyro devices.

Black Powder Pyro Devices

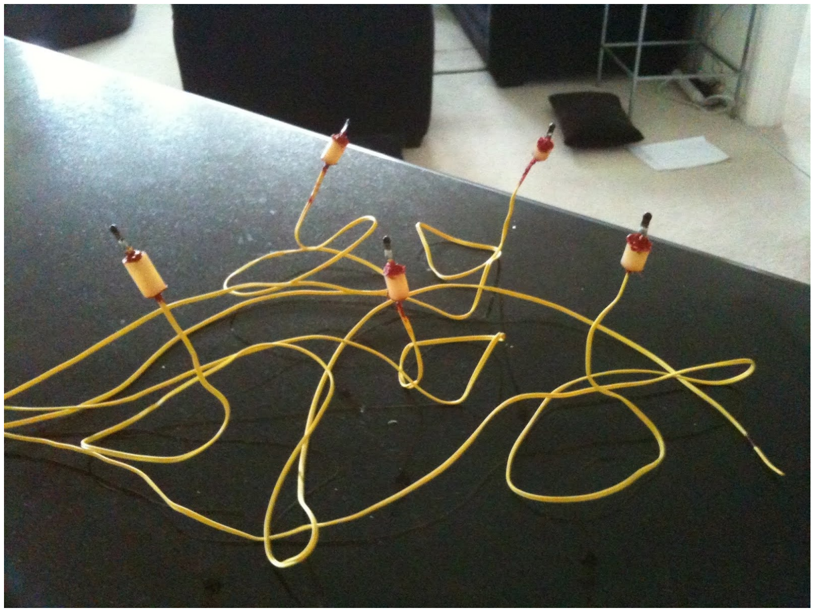
All black powder charges use 2 grams of 4F black powder.

The black powder charges are made from ½" ID, 1/16" wall thickness latex tubing, McMaster-Carr part #5234K35[29]. The ends are stopped with ½" OD latex plugs, about ⅜" long. Each charge had one e-match, entering through one of the plugs. The plug that the e-match enters through is ½" OD, ⅛" ID latex tube. The plug opposite the e-match is ½" OD solid latex. The tubing is cinched down over the plugs with zip-ties, and for extra protection against leakage the ends are sealed with RTV.



The first step in assembling a charge is to run the e-match through the center hole of the ⅛"-ID plug, so that it sticks out about ½". The center hole of the plug is sealed on both ends around the e-match lead with RTV and allowed to fully cure.

[27] http://www.wimpyrockets.com/page16.html
[28] http://www.rouse-tech.com/products.htm
[29] http://www.mcmaster.com/nav/enter.asp?partnum=5234K35

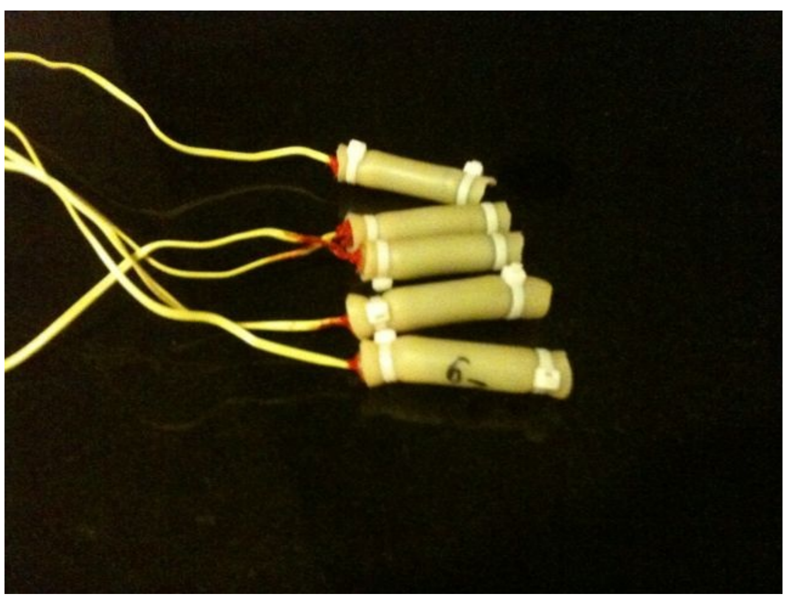


Preparation of Black Powder Charges
Photo: Erik Ebert

Once the e-match plug has cured, the plug is inserted in one end of a 2-inch section of the ½"-ID latex tube and cinched down with a zip-tie.

Next the tube is filled with the black powder, the solid plug is inserted on top of the black powder and cinched down with a zip-tie, and any excess tubing is trimmed off.

Finally, each end of the charge is sealed with a generous amount of RTV and the RTV allowed to cure.



Prepared Black Powder Charges
Photo: Erik Ebert

CD3 Pyro Devices

Each CD3 is is assembled with a 12-gram CO_2 cartridge. They are assembled with potted e-matches, as per the manufacturer's directions for high-altitude flights. Important things to keep in mind are filling the powder well only half-full (as per the addendum in the instructions), careful potting of the match heads, and using plenty of grease on the o-rings and pistons for a good gas seal. For additional protection, RTV is added around the leads of the e-matches where they enter the CD3 body.

Tom Rouse Preparing a CD3
Photo: Melanie Barker

Each CD3 is built with two e-matches, and each avionics bay has two flight computers, so that each CD3 has one match connected to each flight computer.

Since the CD3s are mounted to the nose cone and ISC baseplates, the wiring harness for the CD3s are built with an inline connector that can unplug when the nose cone/ISC ejects. Otherwise the nose cone and ISC would remain tethered to the airframe by the short wiring harness instead of the Kevlar recovery harness. Strain relief (zip-ties) are added on the av-bay side to prevent the av-bay side of the wiring harness from tugging on the flight computers. This isn't an issue with the BP charges because they are not mounted to the nose cone/ISC baseplate, but instead float loose in the recovery bay.

Pyro Inventory

- Sustainer apogee: one CD3 (two e-matches, one to each computer) and one black powder charge (either computer)
- Sustainer low-level: two black powder charges (one to each computer)
- Stage separation (booster ISC): one CD3 (two e-matches, one to each computer)

- Booster apogee: one CD3 (two e-matches, one to each computer) and one black powder (either computer)
- Booster low-level: two black powder charges (one to each computer)

Parachutes

The main parachutes for booster and sustainer are custom-made Fruity Chutes “Iris Ultra”[30] parachutes. These chutes have a toroidal shape that yields a dramatically higher Cd than elliptical designs of equivalent material and packing volume. The booster main is a 48-inch Iris Ultra parachute. The sustainer main is a 36-inch Iris Ultra parachute.

The booster drogue is a conventional 18-inch elliptical chute from Fruity Chutes. The sustainer drogue is a Rocketman[31] R24D.

Deployment Bags

The main parachutes are packed in Rocketman deployment bags. The bags are sized to fit the corresponding airframe, with a 4-inch base diameter bag for the booster and 3-inch base diameter bag for the sustainer. Field surgery was conducted to reduce the size of the flap, saving space in the recovery bays. These bags are simple and highly reliable.

The drogue parachutes are not protected by deployment bags or Nomex pads, again to save space. Care is taken to pack the drogues such that the Kevlar harness sits between the drogues and the pyro devices.

Harnesses

Harnesses are Kevlar, which eliminates the need for additional recovery components such as Nomex pads or sleeves to protect the recovery harnesses, which would take up additional space. The tradeoff is that Kevlar does not have the elasticity of nylon to distribute the shock of recovery device deployment. Kevlar is also weakened by knotting and tends to fail before it becomes visibly frayed, so the harnesses should be completely replaced every few flights.

The booster and sustainer recovery harnesses are nearly identical except for size.

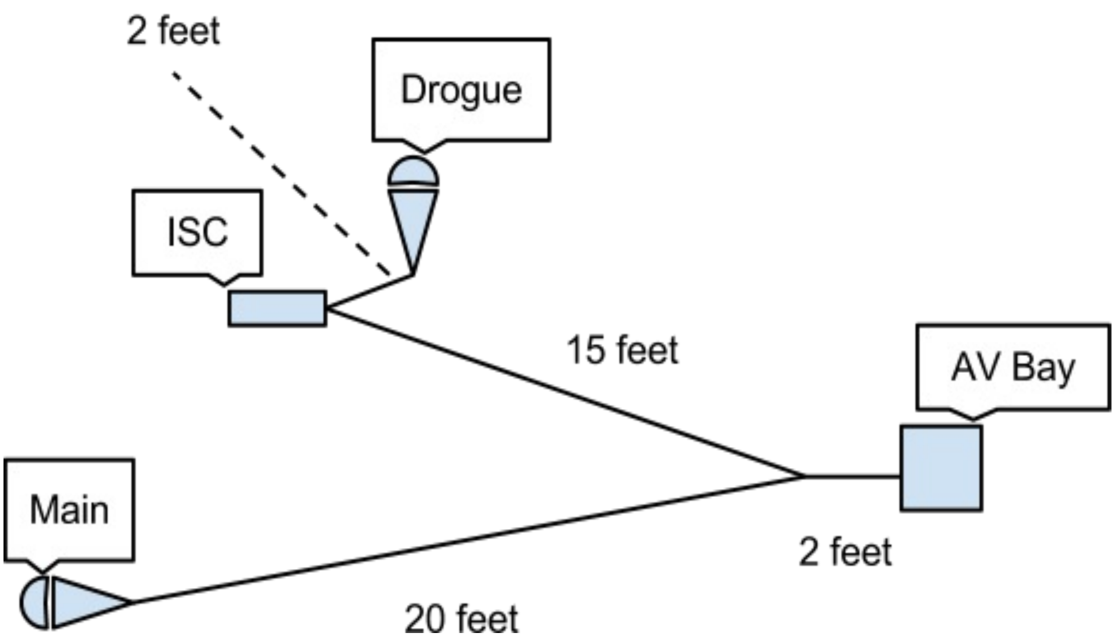
Booster Harness

The main booster harness is constructed of ½” tubular Kevlar. The harness consists of three segments of different lengths. Each segment has pre-sewn loops at each end. The three segments form a Y with a short base and long, unequal arms. The base of the Y is a two-foot segment. The free end of the base is attached to the avionics bay. The two arms branch out from the other end of the base segment. The longer arm of the Y is 20 feet long and attaches at its far end to the nose cone. The shorter arm of the Y is 15 feet long and attaches at its far end to the ISC. The shorter arm on the ISC keeps it safely away from the main parachute, once both

[30] http://fruitychutes.com/buyachute/iris-ultra-chutes-60-to-168-c-18/
[31] http://the-rocketman.com/chutes.html

are deployed.

In addition to the main harness, the drogue is attached to the ISC by a two-foot segment of ¼” Kevlar cord. The cord does not have pre-sewn loops, so bowline knots are used.



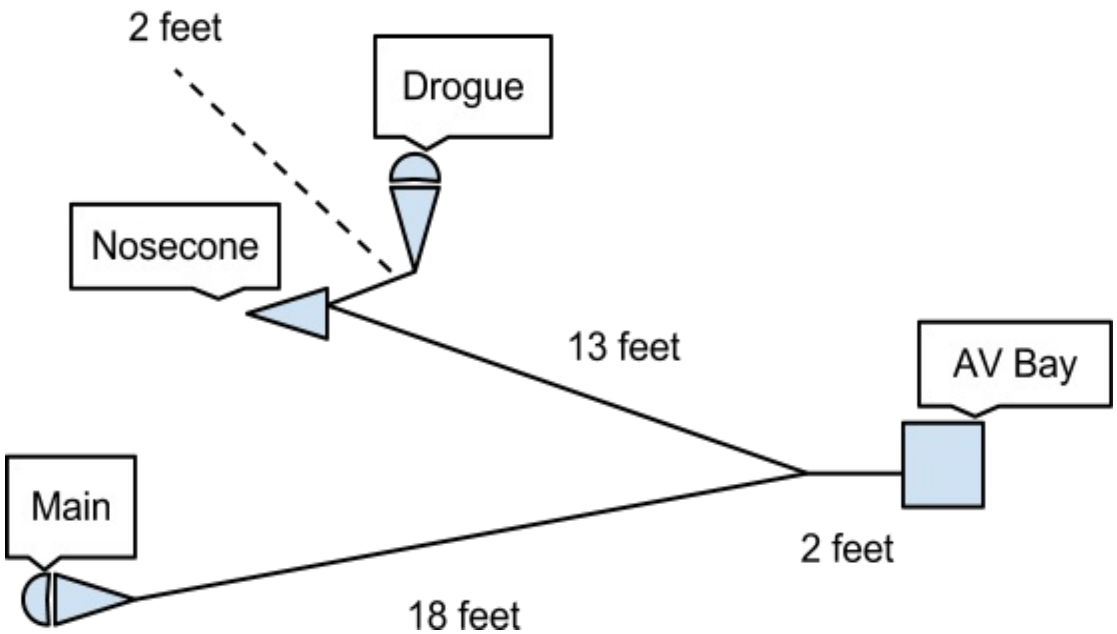
Schematic: Erik Ebert

Quick Links: Don’t Need ‘Em

To save weight, and especially to save space in the recovery bay, no quick links are used. The segments of the harness are assembled by a complicated series of girth hitches, involving passing loops through other loops, which we are thinking of marketing as an executive desktop puzzle.

Sustainer Harness

The sustainer harness is nearly identical to the booster harness, with the nose cone in place of the ISC, except to save additional space both arms of the Y are shortened by two feet (18 feet and 13 feet instead of 20 feet and 15 feet), and the longer arm is constructed from ¼” Kevlar cord terminating in bowline knots instead of ½” tubular Kevlar with pre-sewn loops.



Schematic: Erik Ebert

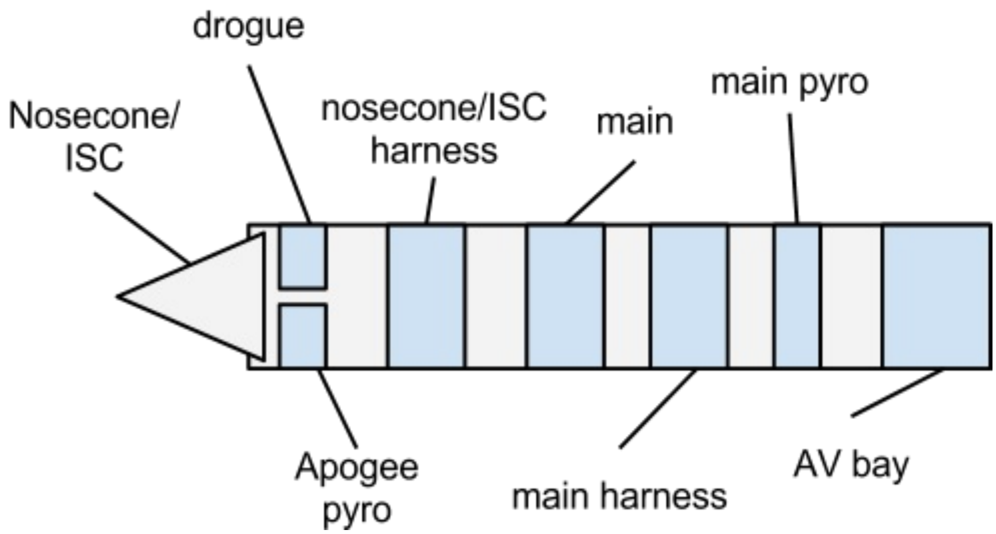
At 13 feet, the nose cone segment of the harness is probably on the short side for deploying in significant atmosphere, especially since Kevlar does not stretch to distribute the deployment shock over time. But for deployment at 100k', 13 feet of harness on the nose cone works perfectly. Since there is virtually no air to grab the drogue, the initial deployment shock is minimal. Pressure on the harness increases gradually as the airframe descends deeper into the atmosphere.

Launch Preparation

The packing order of the recovery components (and the deployment sequence) is the same for both the booster and the sustainer. When the rocket is buttoned up for launch, the order of the recovery components, starting from the forward end of the stage, is as follows:

nose cone/ISC – drogue – apogee CD3/BP – nose cone harness –
main parachute – main harness – low altitude BP – AV-Bay

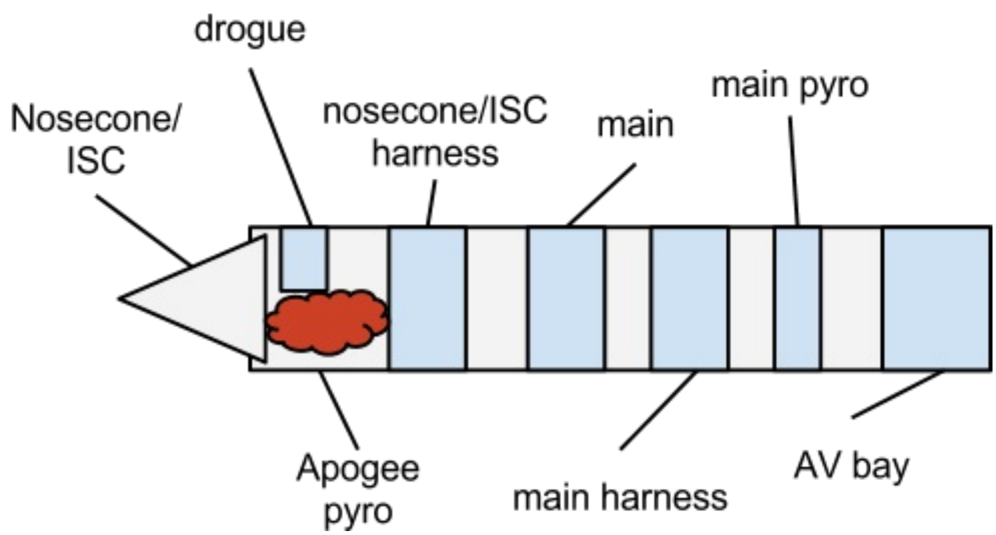
In practice, the drogue, apogee pyros, and nose cone harness are nearly side-by-side, to maximize the use of all available packing volume.



Schematic: Erik Ebert

Apogee Event

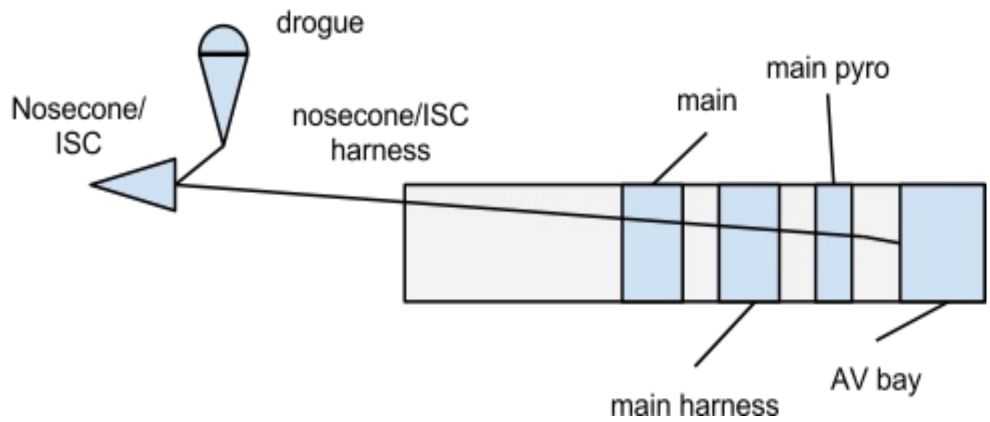
At apogee, the apogee pyro ejects the nose cone or ISC (along with the drogue on its short tether):



Schematic: Erik Ebert

High-Altitude Descent

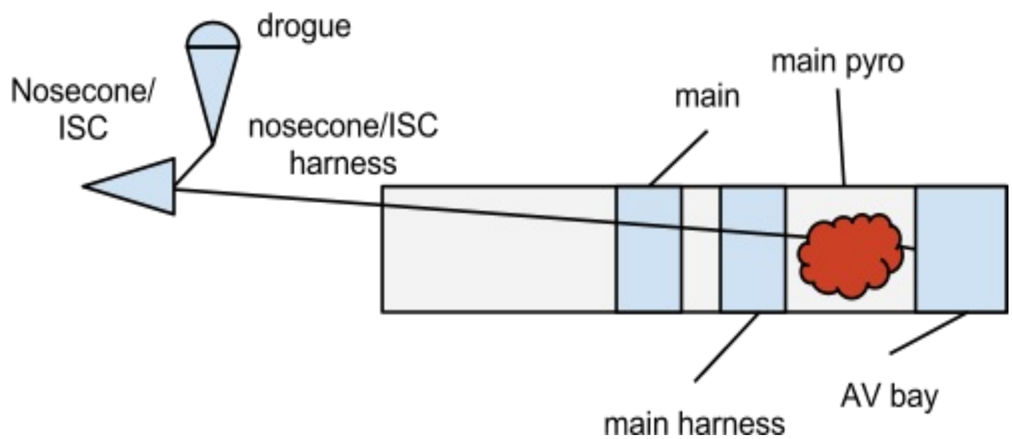
The nose cone harness is connected to the av-bay through its arm of the Y harness and the base of the Y harness. Since the main is on a separate arm of the Y harness, the nose cone and drogue do not exert any force to pull the main out. This configuration allows us to deploy both chutes out of the forward end of the airframe, which eliminates any couplers as potential weak points in the airframe, without requiring any kind of pyro-based reefing device to retain the main.



Schematic: Erik Ebert

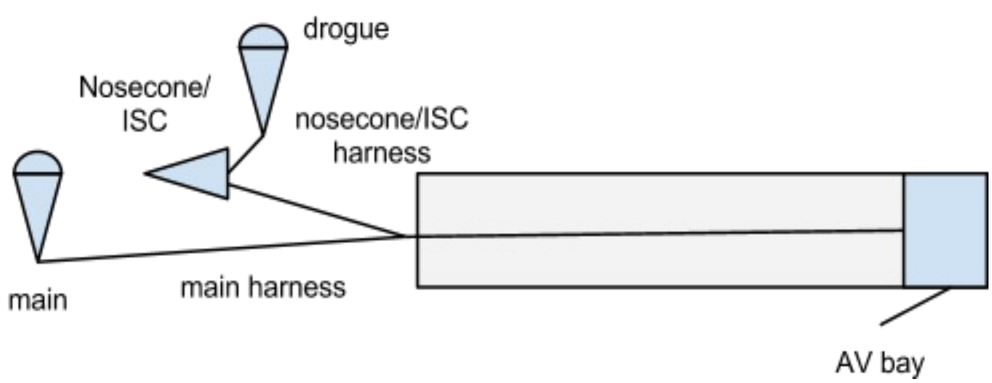
Low-Altitude Event

At a predetermined low altitude (baro-based), the main pyros fire, pushing out the main parachute.



Schematic: Erik Ebert

Low-Altitude Descent



Schematic: Erik Ebert

Packing Sequence

Because of the limited space in the recovery bay, the important aspect of packing the recovery gear is utilizing all of the available three-dimensional volume. Just like mixing propellant, voids are bad. Packing requires three sets of hands to hold various components as they are coiled, compressed, and installed.

1. The harness is assembled and attached to the hardpoints (av-bay, nose cone/ISC, and main parachute). Because we are not using quick links, the harness must be attached to the av-bay before the bay is inserted into the airframe.

David Raimondi Preparing Airframe A
Photo: Erik Ebert

2. The av-bay and motor are inserted into the airframe and tightened down.

3. The 70-cm antenna from the BeelineGPS is taped to the side of the recovery bay. The antenna extends into the recovery bay so it must be taped to the side of the airframe to protect it from being crumpled when the recovery bay is packed. Conversely, when unpacking the airframe post-flight, the tape must be removed before the av-bay is

removed. Gaffer tape is used, which is similar to duct tape, but does not leave a tape residue. It turns out this is an easy step to forget. On various occasions we either forgot to add or remove the tape, requiring some quick field repair to the antenna. We settled on leaving a strip of gaffer tape on the end of the airframe to remind ourselves. Lesson learned: Don't forget to add/remove the tape! Also, gaffer tape doesn't stick to teflon spray lube!

4. The main parachute lines are untangled, and the parachute is packed into the deployment bag. The apex of the chute is tied to the Rocketman bag's built-in harness. The parachute is stretched out and stuffed a handful at a time into the bag, starting at the apex. Everybody seems to have their own opinion on the best way to pack a parachute, but in our collective opinion, this is more reliable than rolling, z-folding, or other strategies, and results in the parachute tumbling out as soon as the bag is opened, with no tendency for the parachute to get stuck in the bag. At this point the parachute is compressed into the bag with a hydraulic press[32], or the nearest available human equivalent. The base diameter of the deployment bag is chosen to match the ID of the airframe, so the result is a cylinder the diameter of the airframe and as short as possible.

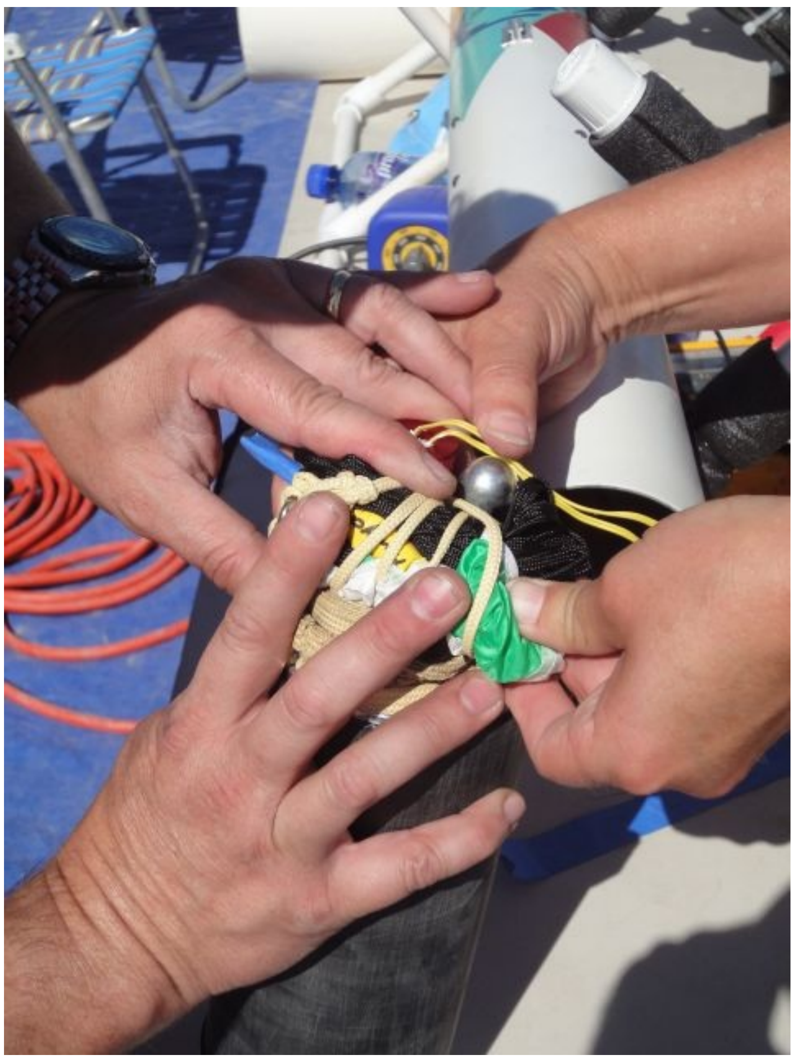
5. The shroud lines and main harness are packed into the deployment bag. These are coiled into the bag to form a flat disc on top of the parachute. The main harness is then carefully coiled into a flat disc and placed on top of the shroud lines, and the bag is again compressed and then closed. It isn't strictly necessary to pack the harness inside the bag, since the harness is Kevlar, but it doesn't hurt. More importantly, it keeps the harness coiled flat and taking up minimum space as the main is inserted into the airframe.

6. The main chute is inserted into the airframe. Make sure that antenna is taped! The low-altitude BP charges get tucked against the av-bay. Several things have to run past the main: The base of the Y harness, the apogee BP charge, and the wiring harness for the apogee CD3. Taking note of where they leave the av-bay, one person holds them out of the way to that side while another person stuffs the main deployment bag into the airframe against the av-bay. It is important that the base of the Y harness remains fairly taut and the main harness runs from the Y point back to the main, so that the drogue harness can put tension through the base of the Y to the hard point without tugging on the main harness. This is where a +3 Stick of Packing is useful to compress the main deployment bag tightly against the av-bay to make enough room for the nose cone/ISC harness, the apogee pyros, and the nose cone/ISC shoulder. *This is also a good time to lay out and prep all the tools for drilling, tapping and inserting the shear pins before packing the nose cone/ISC.*

7. The CD3 wiring harness is connected and the nose cone/ISC harness, drogue

[32] http://www.youtube.com/watch?v=nyFYolprgBA

parachute, and apogee BP charge are tucked around the apogee CD3. The nose cone harness is coiled into a flat disc, and the disc is tucked in a semicircle around the CD3. The drogue is z-folded and the shroud lines wrapped tightly around to compress it, then the bundle is tucked around the CD3. Normally, you wouldn't pack a chute this way, but it keeps the bundle as small as possible, and it is a small chute with no deployment bag, so it will have plenty of time to unroll. Finally, the apogee BP charge is tucked against the CD3, keeping it away from the drogue as much as possible, and with as much "stuff" between it and the drogue as possible. While doing this, keep in mind the order that the harnesses will uncoil, to try to avoid them wrapping around and snagging the CD3. The harnesses should be tucked *next to* the CD3, not wrapped around the CD3. The end result is a cylinder the diameter of the airframe and as short as possible, utilizing all available volume.



Preparing Booster A
Photo: Erik Ebert

8. The nose cone/ISC and associated harnesses are inserted into the airframe. Double-check that you've got the tools out for the next step, before you insert the nose cone or ISC. If you've done the previous steps well, it should just fit, with a little bit of force needed to hold the nose cone or ISC flush against the airframe. In the case of the sustainer, it took a lot of force to hold the nose cone flush against the airframe.

9. While one or two people hold the nose cone or ISC flush against the airframe, a third person installs shear pins. You already have all the tools (drill, tap, screwdriver, and shear pins) prepped and laid out, right? It's almost impossible to line up previous holes, so new holes are drilled and tapped each time. For both the booster and sustainer, two 2-56 nylon screws are used as shear pins.

3.8 Motors and Ignition

We desired long burn motors for both booster and sustainer, and we were committed to certified motors. One of our team had flown both the CTI N1100 and the Aerotech N1000 in the same airframe and, based on his experience, we chose the N1000 as the better motor for the booster. At the time of our design, only one commercial motor–the CTI M840–had a burn profile that matched our needs. The Aerotech M685 was under development but not yet certified. Both motors fit in the same case, allowing us to build the airframe to fit either based on availability. The M685 promised a bit more burn time and incrementally more total impulse, and our simulations suggested that difference could provide up to 5k' additional altitude, so it was our first choice, if available.

Sadly, there was no certified motor or forward closure that supported head-end ignition, so we needed to create a way in a minimum diameter airframe to do aft-end ignition reliably. As on earlier projects, we solved the problem of aft-end ignition by running copper strips along the side of the sustainer motor (insulated from the motor casing by Kapton tape) to create a conductor pair from the avionics bay to the motor nozzle. We then soldered connections from the avionics bay to the forward end of this tape conductor, and from the aft end of the tape conductor to the igniter wires for the sustainer.

The igniters are an e-match dipped in Boron/Potassium Nitrate/Nitrocellulose lacquer and inserted into a thin plastic bag containing copper thermite. Boron/Potassium Nitrate is a common combination used by NASA[33] to light motors in the vacuum of space. Copper thermite is known for its high heat and rapid lighting characteristics.

The igniter bags are formed on mandrels. The mandrels are a ½" dowel for the booster and 5/16" dowel for the sustainer. One wrap of 1-mil plastic is used to form the bag, and the bag is sealed with cellophane tape at the overlapping edge. Some of the bag is pulled back from the mandrel and a dipped e-match inserted. The e-match is secured with cellophane tape, forming a taper. The bag is then removed and filled with copper thermite at the rate of 1 gram per 1000 N*s. The

[33] http://en.wikipedia.org/wiki/Pyrotechnic_initiator

end is sealed with cellophane tape and tapered.

Each igniter is taped to a ⅛” wooden dowel to make insertion and retention easier.

David Raimondi, Becky Green, and Jim Green, Installing the Igniter
Photo: Erik Ebert

3.9 Launch System

Rail vs. Tower

An optimal tower launch would have reduced launch friction, but would have complicated the loading of the rocket. We also believed that we would get better guidance from the existing AeroPac 12-14’ rails because the sustainer and booster are different diameters, so we opted to fly from a rail.

Rail Guide Attachment

The booster had conformal rail guides attached to the airframe at the aft end and about 3.5 feet up the airframe. These were later field-replaced with standard Delrin buttons mounted on screws tapped into the booster av-bay aft bulkhead and the motor aft closure, as described in the flight results.

3.10 GPS, Telemetry, and the Virtual Classroom

Any flight going this high must have reliable, real-time telemetry, both for the simple necessities of recovery and for real-time assessment of the flight status. For our mission goals, the Carmack Prize required trusted GPS documentation of the flight. Two previous attempts at the Carmack Prize (Qu8k and FourCarbYen) encountered challenges getting good GPS data, despite flights that likely got them well above the 100k' AGL target. However, our team had substantial experience in various GPS systems, and we were confident that we could get good GPS data.

Our GPS system of choice was the 70-cm Beeline GPS, particularly with its 2012 upgrade to the u-blox 6 GPS module and an increase in transmitter power from about 15 mW to 100 mW. Several team members had prior success making use of the Beeline, and our calculation of the link budget for the radios suggested we would have continuous telemetry coverage during the expected flight. As insurance, we also included a DIY u-blox 6 GPS data recorder on the first flight, but the Beeline performed superbly, so the DIY GPS was not flown again.

We anticipated that we would get GPS data in three ways:

- from onboard storage of the GPS position at a 1-Hz rate. Due to inherent limitations of the u-blox 6 GPS module, we did not expect GPS positions at speeds exceeding 500 m/s or at altitudes exceeding 50 km to be recorded.
- from real-time 70-cm APRS[34] telemetry at a 0.2-Hz rate, to handheld radios used by team members. We expected that we would get decent coverage with the more powerful Beeline's, even using simple rubber-ducky antennas on the handheld radios.
- from real-time telemetry at 0.2 Hz to the Virtual Classroom base station. Described in greater detail in the Appendix, we designed the Virtual Classroom as a high performance base station for high altitude flights. In particular, we configured it with specialized 70-cm antennas[35] (originally designed to communicate with LEO satellites) that offer circular polarization and 17-18 dB net gain over a hemispherical coverage area. These feed two APRS-compatible radios, a Kenwood TH-D7 and a Kenwood TM-D700. The radios, in turn, feed computers that record the track and forward data to the international APRS-IS [36] database for Internet distribution.

The Virtual Classroom is AeroPac's mobile ground station for high altitude rockets and balloons. Based on a donated veteran television coverage van, the VC has self-contained power for both stationary and mobile operation. It is based on an original idea from Prof. Bob Twiggs to provide

[34] http://www.aprs.org
[35] http://www.antennas.us/store/p/390-UC-4364-513-UHF-Amateur-Satellite-Antenna-with-built-in-LNA.html
[36] http://www.aprs-is.net

a virtual window into remote events, such as high altitude rocket launches.

Virtual Classroom
Photo: Ken Biba

The VC provided us some fundamental tools for this project:

- backhaul to the Internet via a satellite backbone;
- a WiFi hotspot footprint gatewayed to the Internet via satellite;
- high performance 70-cm APRS tracking tools oriented to cover the sky and gatewayed to APRS-IS for Internet access to the real-time flight tracks of sustainer and booster; and
- three network cameras' views of the launch, to be shared via real-time webcast.

3.11 Science Payload

The earliest brainstorms about this project included a goal of carrying a meaningful science payload, in the spirit of an ARLISS "extreme" project. Also, our AeroPac team has strong ties to a team of developers who have been experimenting with Android-powered balloon and rocket payloads using Nexus mobile phones and open-source software. Having such common interests and goals, we decided to adopt an Android-based system as our target science payload.

A standard Nexus phone includes a wide range of interesting physical sensors, including a barometer, magnetometer, GPS, accelerometer, and gyroscope. The phone's operating system and development environment are open source, which gives developers a lot of latitude to customize the system for the unique requirements of the payload. These factors have made the Nexus a popular foundation for orbital CanSat projects.

The target payload consists of a Samsung Galaxy Nexus phone; a 5-watt, 2-meter amateur transceiver; an 11.1V LiPo pack; and a “IOIO” board (pronounced “yo-yo”) to extend the I/O capabilities of the phone. A magnetic switch enables the radio and IOIO board, which in turn signals the phone to begin recording sensor data. Software in the phone encodes sensor data into APRS audio frames and keys the radio (via the IOIO board) to transmit them. The payload has three mission goals:

1. Document the flight as seen by the Nexus’s sensors and locally store that flight record aboard the phone.
2. Transmit a subset of the flight sensor record encoded in APRS frames via the 2-meter radio.
3. Act as a 2-meter radio beacon to assist in recovery if the primary 70-cm recovery beacon failed or could not be heard due to distance.

The development team also designed a ground station for a Nexus 7 tablet to decode the audio stream directly from an amateur radio receiver and plot the received payload beacons in Google Earth, in real time.

The payload flew aboard one of the test flights and one of the full mission flights and successfully streamed live tracking data. Details and source code for the payload system will be published separately.

3.12 Painting

We painted the two airframes slightly differently.

Airframe A was painted by a local artist, Tom Biba, and reflects a theme of the history of modern rocketry. Both sustainer and booster have a three-color spiral theme, where each band incorporates details representing the history of science and rocketry from the perspective of one of three cultures: Europe, the Americas, and Asia.

Robert Goddard - Americas

Qian Xuesen - Asia

Konstantin Tsiolkovsky - Europe

Photos: Ken Biba

Theme	Scientist	Narrative
Europe	Konstantin Tsiolkovsky[37]	Beginning with the ancient Greeks, Europe has played a key role in laying the foundations of modern science, leading to the work of Tsiolkovsky in defining the basic mathematics and physics of space flight, thereby laying the foundations for modern European space flight.
Americas	Robert Goddard[38]	Beginning with the Incas, Mayans and Aztecs, American cultures have dreamed of the sky and constructed mathematics and predictions. Robert Goddard was the American scientist who laid the foundation for liquid-fuel rocket motors.
Asia	Qian Xuesen[39]	Asian cultures mapped the sky and invented fireworks, culminating in Qian Xuesen, who contributed strongly to the technology of the Space Shuttle before becoming the parent of the modern Chinese space program.

Airframe B was painted in “Nexus” livery as a reflection of our first science payload.

[37] http://en.wikipedia.org/wiki/Tsiolkovsky
[38] http://en.wikipedia.org/wiki/Robert_H._Goddard
[39] http://en.wikipedia.org/wiki/Qian_Xuesen

4.0 Flight Program

The flight program was designed to incrementally test elements of the system, including airframes, staging, recovery, and electronics, to identify improvements and build confidence for full 100k'-capable flights. In broad strokes, the flight program consisted of three incremental configurations:

- Sustainer-Only Test
- Booster/Sustainer Stack Test (reduced impulse)
- Full 100k'-Capable Flight

For each flight, we provide a description of the flight configuration, the resulting data, and then our collective analysis of the data, including the results–changes that we made to the following flights.

4.1 Sustainer-Only Test Flight

We conducted a test flight of the Airframe A sustainer at the AeroPac *Mudroc* launch at Black Rock on June 16, 2012.

Configuration

Flying only the sustainer required some deviations from the designed flight configuration, namely:

- The flight was launched from an 8-foot tower, as the sustainer airframe lacks rail guides.
- A 2-grain 75-mm AeroTech K560W was used to limit the altitude and velocity.
- The shorter motor necessitated an extension rod between the avionics bay and forward closure.
- The sustainer motor was ignited from launch control, so the avionics only controlled deployment.

The recovery system consisted of a 6-foot nylon streamer for apogee and a 36-inch Fruity Chutes Iris (toroidal) main parachute.

The payload was a single Beeline 70-cm GPS transmitter (#157), a GoPro HD Hero2 with WiFi Bacpac, and an early revision of the Nexus science payload.

For this flight, two Raven units (#1383, #1388) were configured as follows:

Event	Charge	Trigger
Apogee	12 grams CO_2 (CD3)	V < 0
Backup Apogee	2 grams Black Powder	Time > 31 s

Main Parachute	2 grams Black Powder	Alt < 2000’, Pressure Increasing, V < 400 fps

Although the expected apogee was well within the operational range of the Raven’s barometer, we configured the Apogee trigger to use only the accelerometer, as this was our anticipated configuration for the full mission flights. The single Apogee CD3 used two e-matches, one connected to each Raven unit. There were two BP charges for main parachute ejection, one for each unit. The single Backup Apogee charge was only connected to one of the Ravens (#1388).

During flight preparation, we noted that the gross mass exceeded the simulation by over a pound. This led us to an error in the simulated component masses. Once the simulation masses were trimmed out, we determined that no additional nose ballast was required for stability with the K560W.

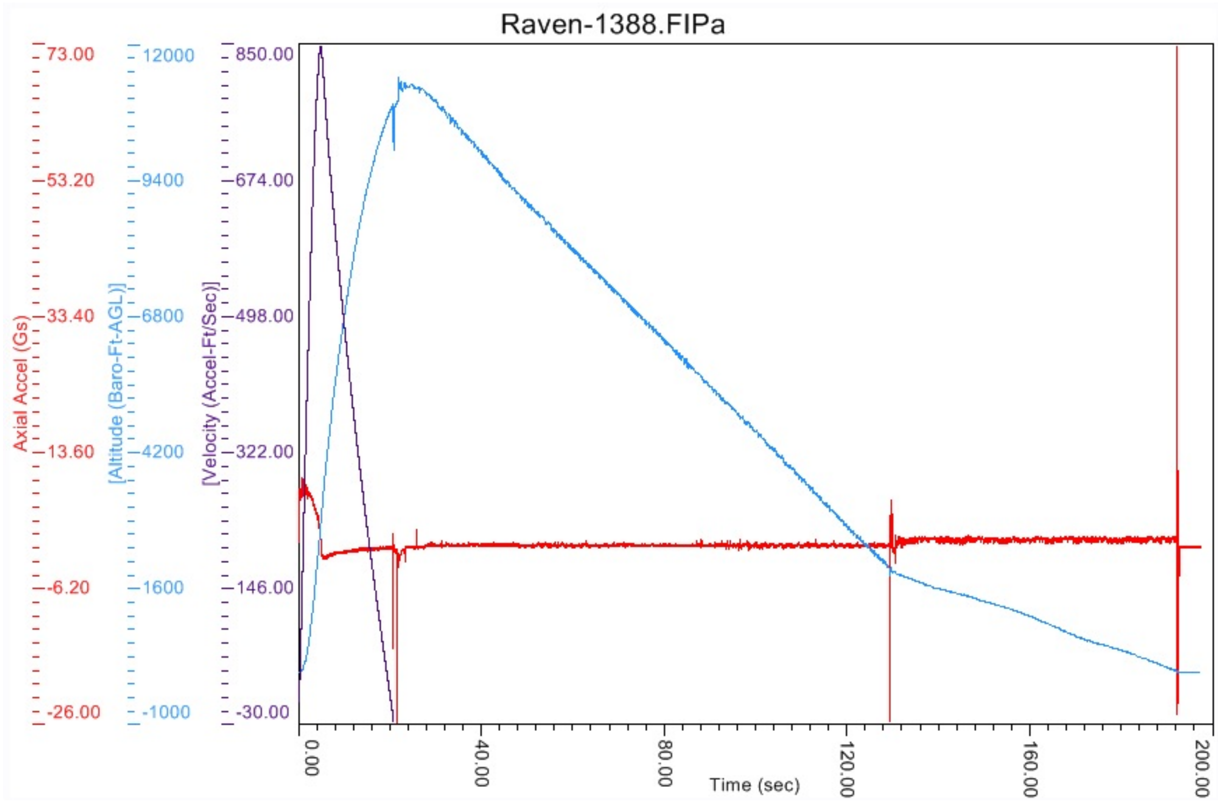
Flight Data

At liftoff, the sustainer appeared to bounce inside in the launch tower, leading to a somewhat off-vertical trajectory, but the flight appeared otherwise nominal. Descent on the main parachute was easily visible and appeared normal. Recovery was 1.0 mile southeast of the launch site. All charges were blown. The streamer was almost entirely tangled in the nose cone shock cord.

The Beeline recorded a maximum altitude of 12,706 feet (3873 m) AGL, but the highest fix was the first fix after regaining lock (following 21 seconds lost), so it’s possible that apogee was much higher.

Raven unit #1383 did not record a complete flight. The flight log stops exactly as the apogee charge should have fired. The Raven recorded no loss of battery voltage or other anomalies. From bench tests, we would expect the large capacitor on the Raven to ride out (and record) at least a few seconds of battery loss, so the cause is a mystery.

Raven unit #1388 did record a complete flight. Of particular note, the purple line (accelerometer-integrated axial velocity) reaches zero and triggers the apogee event while the blue line (baro altitude) is still increasing.



Sustainer Test Flight – Raven Data

Video from the sustainer indicates that the roll rate was <2 Hz.

Analysis and Results

Although Raven #1383 did not record the flight past the apogee trigger, its main BP charge was blown. We did not know whether this was caused by sympathetic detonation from the neighboring BP charge fired by #1388, or whether #1383 actually completed its flight events and just failed to record a complete log. (Later tests shed some light on this question, with the failure of #1387 in the stack test flight.)

> **Result:** Raven #1383 was quarantined and did not fly again.

Both Raven plots showed that accelerometer-based apogee detection triggered while the barometer-measured altitude was still increasing at ~200 fps. Examining data from other Raven-based flights (including baro-based flights), we found the accelerometer nearly always integrates to zero velocity well before real apogee. This indicates that the Raven's accelerometer-based apogee detection is not usable on longer flights.

> **Result:** Reluctantly changed to baro-based apogee detection for test flights and all boosters going forward, but maintained skepticism regarding its reliability above 100k'. Started a search for alternatives.

We did not know whether the sustainer needed an apogee recovery device. The tangled streamer yielded a descent rate of ~100 fps, and the video indicated that the airframe fell in a flat spin, but the tangle caused concern.

> **Result:** Installed a small drogue for future flights.

We were able to visually track the sustainer descent on main parachute for this flight, but as the main descent only lasted 60 seconds, we wanted to give ourselves more time to get a good GPS track in advance of landing on future flights, and also a little more insurance time to get the main parachute unfurled.

> **Result:** Raised the deployment of the main parachute to 3000' AGL.

The apogee altitude was somewhat less than simulations had estimated, but the Raven's early apogee deployment clearly cut short the flight. Extrapolation suggested that the sustainer performance was on the high side of expectations.

> **Result:** Confirmed our expectations regarding Cd and gained confidence that the design could exceed 100k'.

4.2 Full Stack Test Flight

We conducted a two-stage test flight of the Airframe A booster and sustainer at the AeroPac *Aeronaut* launch at Black Rock on August 4, 2012.

Photo: Ken Adams

Configuration

This flight deviated from the mission configuration only to limit the total impulse:

- A 2-grain 75-mm AeroTech K560W was used in the sustainer.
- A 3-grain 98-mm AeroTech M1419W was used in the booster.
- The shorter motors necessitated extension rods between the avionics bays and forward closures.

This flight configuration yielded a full stack performance that closely modeled the expected speed of the staging event, just over Mach 1, allowing us to test staging while limiting total altitude.

The sustainer recovery system consisted of a Rocketman R24D drogue and a 36-inch Fruity Chutes Iris (toroidal) main parachute. The booster was drogueless with a 48-inch Fruity Chutes Iris (toroidal) main parachute. While packing, we found that the booster's recovery bay would not accommodate a drogue, so we eliminated it at the last minute.

The payloads were Beeline 70-cm GPS transmitters (#157 in sustainer, #154 in booster), and GoPro HD Hero2 cameras with WiFi Bacpacs in both booster and sustainer. This flight replaced the sustainer's science payload with an R-DAS Tiny unit (plus additional nose ballast) to evaluate it as a possible Raven replacement.

Two Raven units (#1387, #1386) were configured for the booster:

Event	Charge	Trigger
Sustainer Separation	12 grams CO_2 (CD3)	Time > 8 s
Apogee	16 grams CO_2 (CD3)	Pressure Increasing, V < 400 fps
Backup Apogee	2 grams Black Powder	Time > 18 s (8 + 10)
Main Parachute	2 grams Black Powder	Alt < 2000', Pressure Increasing, V < 400 fps

As the Raven supports only one timer, the backup apogee trigger was constructed based on the separation timer, plus a 10 second delay. Only unit #1387 controlled backup apogee.

Two Raven units (#1384, #1388) were configured for the sustainer:

Event	Charge	Trigger
Motor Ignition	K560W	Time > 11 s
Apogee	12 grams CO_2 (CD3)	Pressure Increasing, V < 400 fps
Backup Apogee	2 grams Black Powder	Time > 50 s
Main Parachute	2 grams Black Powder	Alt < 2000', Pressure Increasing, V < 400 fps

Baro-based apogee detection was used because of our experience on the sustainer test, and because the expected apogee was well within the Raven barometer's operational range. Although their configurations were identical, one Raven controlled motor ignition, and the other controlled backup apogee.

During packing, we found that the ISC had expanded due to playa midday heating and would no longer fit in the booster. It required nearly a day of sanding to fit, made difficult by the hot conditions.

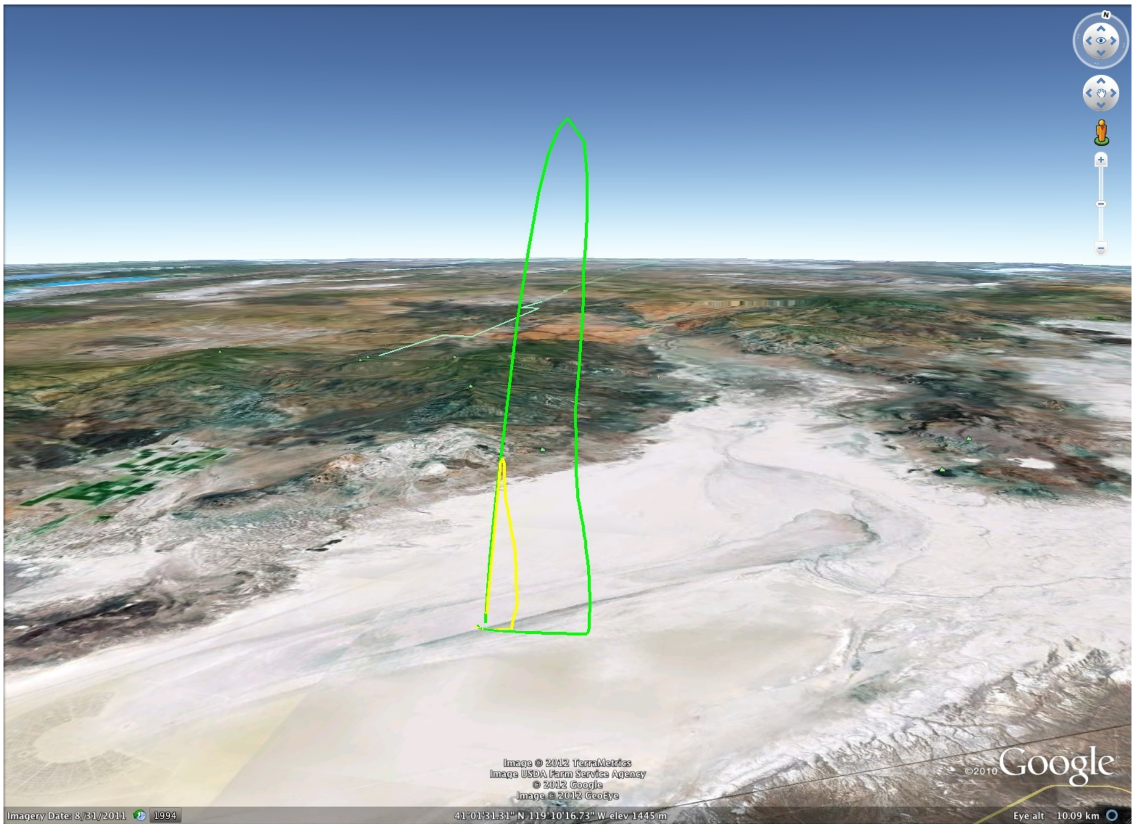
Flight Data

The flight was near vertical, but with slight coning of the full stack, followed by successful sustainer ignition. We had not precisely aligned the launch rail to vertical and the slight tilt is easily seen in photos.

The booster was recovered 0.4 miles east of the launch site. It had a slight chip in the forward body tube. All BP charges were blown, but the apogee CD3 was not. The sustainer separation piston broke its Kevlar leader and separated from the coupler, but was found near the booster.

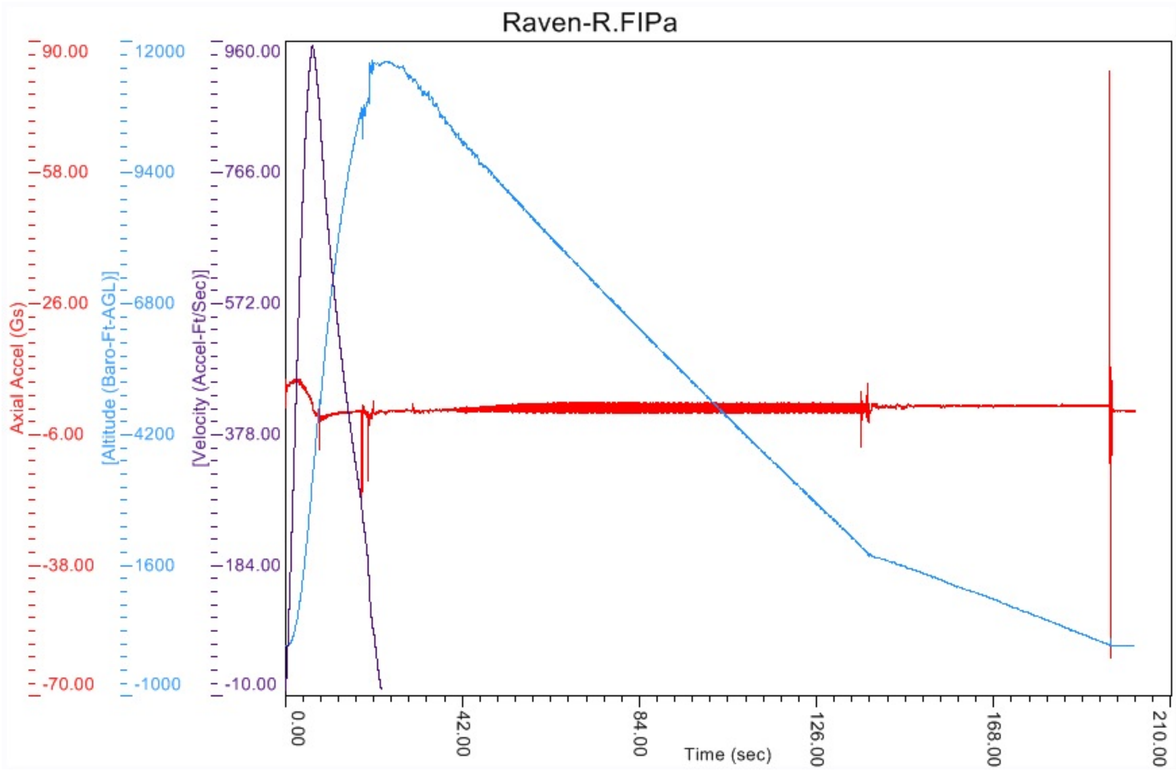
The sustainer was recovered 1.5 miles east of the launch site. All charges were blown.

The internal GPS logs from the flight were lost due to an issue with the Beeline (which was later resolved by a new firmware fix from the manufacturer), but the APRS gateway in the Virtual Classroom recorded sparse tracks. These tracks indicate that the rocket's angle from the pad was less than 8° from vertical when staging occurred, and less than 10° when the GPS regained lock during coast. Sustainer apogee was at 34,414 feet (10490 m) AGL, 12° off vertical and 1.3 miles downrange from the pad. Booster apogee was 12,493 feet (3808 m) AGL.



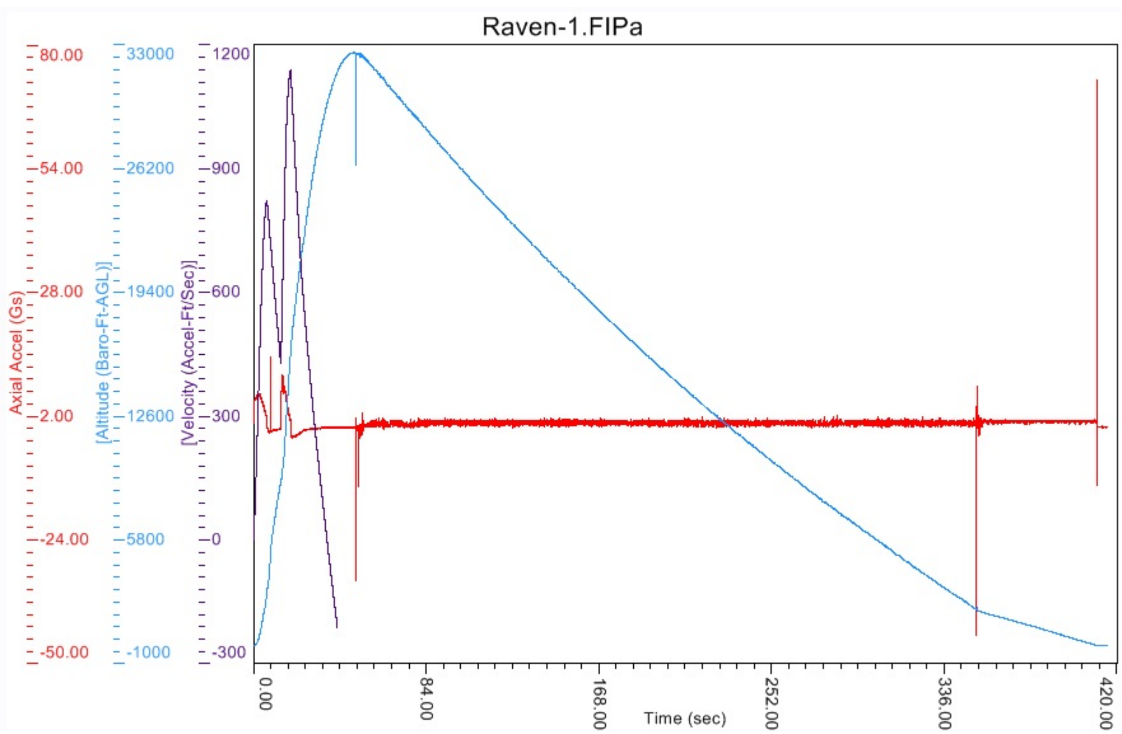
Full Stack Test Flight – APRS Tracking

The booster Raven unit #1387 failed to record a complete log. Again, the log stopped immediately at the point of the first event (sustainer separation), and again no loss of battery voltage was recorded. The other booster Raven showed an early apogee deployment. Note the ejection event occurred as the blue altitude line was still increasing.



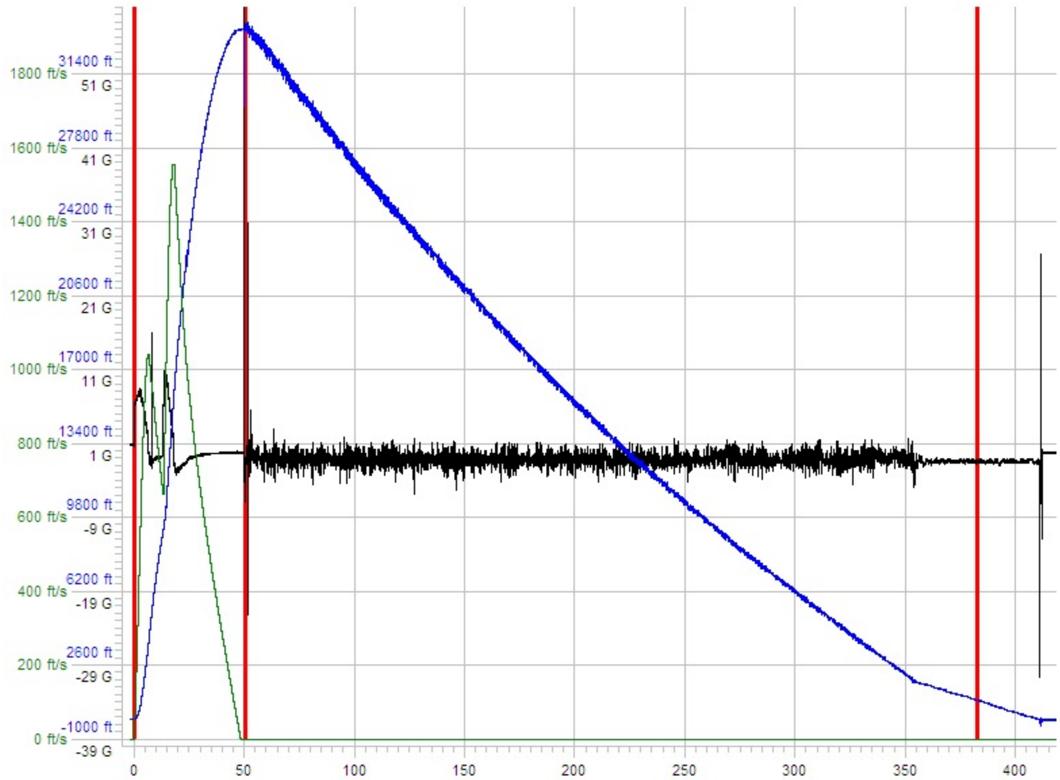
Stack Test Flight – Booster Raven

The sustainer Raven units both recorded nominal flight profiles with very similar data.



Stack Test Flight – Sustainer Raven

The R-DAS unit in the sustainer also recorded a nominal flight profile.



Stack Test Flight – R-DAS (Flying as Sustainer Payload)

The sustainer video[40] showed a nominal flight. The roll rate of the stack was <2 Hz, and the roll rate of the separated sustainer was <2 Hz in the opposite direction.

Analysis and Results

Although booster Raven #1387 failed to record a complete log (much like #1383 in the previous test), we were able to determine that this unit continued to fire events well after the log stopped. Due to an error in the simulation, we had configured the backup apogee event for the booster too early, at 18 seconds. The backup apogee charge was attached to unit #1387. The plot from Raven #1386 indicates that the booster was still climbing at 18 seconds, but that the connection to the apogee charge was lost and a pressure and acceleration spike seen just after 18 seconds. This indicates that #1387 fired the backup BP charge on schedule, even though its log stopped 7 seconds earlier. This also explains why the booster's apogee CD3 was never fired, since the wiring harnesses from the avionics to the CD3 were disconnected by the deployment. We suspect whatever malady affected #1387 was also at fault in the failure of #1383, as the failures appear very similar, but we do not know the root cause.

[40] http://www.youtube.com/watch?v=14P7pG_IOL4

Result: Although we suspect it fired all events, Raven #1387 was quarantined and did not fly again.
Result: Simulation error corrected to reflect booster's expected apogee time.

When the sustainer separation charge fired, the sustainer recorded a 14-G positive axial acceleration. The booster recorded a 10-G negative axial acceleration. Both of these spikes correspond to similar deviations in the barometric pressure curves.

Result: Confirmed that a 12-gram CD3 is very effective at separating the sustainer. Drilled vent holes in the piston to keep the piston from detaching.

Upon further investigation, we found that Delrin's coefficient of thermal expansion indicates that the ISC expands by 0.010" in OD over a 60° F swing in temperature. The same swing leads to a 0.007" increase in the ID of the socket for the sustainer motor.

Result: We further machined the ISCs and ran heat soak tests to verify fits over a range of temperatures. We also cut grooves into Airframe B's ISC such that it could be easily sanded to fit in the field, if necessary. Going forward, we kept a close eye on the temperature of the coupler to limit expansion, and painted the upper sections of the boosters white to reflect heat.

We determined that the slight zipper in the booster was caused by the early timing of the backup apogee charge. Regardless, we decided that a drogue would also be a good addition. The booster was too tightly packed to fit any extra recovery gear.

Result: We reworked both ISCs to remove extra length, convert to an aluminum back plate, and resize the piston to accommodate only a 12-gram apogee CD3 cartridge. We also changed the layout of the CD3 cartridges to provide a more efficient packing arrangement.

We knew that the pad and rail were slightly off-vertical at launch, but it was difficult to get it adjusted correctly in the field. We attributed some of the off-vertical trajectory to that initial lean.

Result: Added a digital level to the field kit and added a checklist item to align the rail before each flight.

Although there was slight coning in the stack, we expected that the mass distribution of the full mission motors would moderate the coning and we were very encouraged by the verticality of staging and apogee.

Result: We decided that our basic staging architecture was sound and that no further action to ameliorate coning was required.

The two sustainer Raven units showed accelerometer-based apogee at 15 and 25 seconds in advance of baro apogee, respectively. This further confirmed to us that the Raven's accelerometer is not suitable for apogee detection. The difference between the two units suggests that the accumulated error cannot be overcome with a fixed delay.

> **Result**: We decided to replace at least one Raven unit and only rely on baro-based apogee detection for all future Raven programming.

The R-DAS accelerometer detected apogee at almost exactly the same time as the Raven's barometer, validating it as a possible replacement for the sustainer on 100k' attempts, where we believed the sustainer would exceed the practical range of barometer-based deployment. However, we were reluctant to replace both of the Raven units as they were already tested and integrated, and we had developed a good understanding of their strengths and limitations. Also, the R-DAS is expensive and difficult to procure on short notice.

> **Result:** We replaced just one of the Ravens in each sustainer with an R-DAS, keeping one Raven in each as a backup system. We also set about determining an appropriate configuration for the Raven on the 100k' attempts.

The Beeline logs were lost due to a feature of the firmware that normally restarts logging when the unit is powered up. Because of the challenge of determining which avionics are powered on or off by the magnetic switches, the Beelines got power cycled several times while trying to disarm the Ravens, and they overwrote the flight logs.

> **Result:** Greg Clark from BigRedBee developed a new feature for us that requires the log to be manually erased, if so configured.

The booster's GoPro did not record a valid video because the SD card had somehow not seated, or got unseated during the flight.

> **Result:** As a precaution, we placed gaffer tape over the SD card slot and WiFi Bacpac connector on future flights. This also gave the camera a bit more friction and helped seat it in the clamps.

4.3 ARLISS/XPRS Full Flight 1

We conducted a full mission flight of Airframe A at the AeroPac *ARLISS* launch at Black Rock on September 11, 2012.

Jim Green, Becky Green, Ken Biba, David Raimondi, Erik Ebert & Pumpkin, Casey Barker
(Tom Rouse and Steve Wigfield not shown)
Photo: Melanie Barker

Configuration

This flight used the full complement of motors, including the newly certified AeroTech long-burn 75mm.

- A 6-grain 75-mm AeroTech M685W was used in the sustainer.
- A 6-grain 98-mm AeroTech N1000W was used in the booster.

The sustainer recovery system consisted of a Rocketman R24D drogue and a 36-inch Fruity Chutes Iris (toroidal) main parachute. The booster used an 18-inch Fruity Chutes elliptical drogue and a 48-inch Fruity Chutes Iris (toroidal) main parachute. Packing was very tight.

The payloads were Beeline 70-cm GPS transmitters (#157 in sustainer, #154 in booster), and GoPro HD Hero2 cameras with WiFi Bacpacs in both booster and sustainer. The sustainer's science payload was replaced by ballast weight for this flight.

Two Raven units (#1386, #1388) were configured for the booster:

Event	Charge	Trigger
Sustainer Separation	12 grams CO_2 (CD3)	Time > 14 s
Apogee	12 grams CO_2 (CD3)	Pressure Increasing, V < 400 fps
Backup Apogee	2 grams Black Powder	Time > 38 s (14 + 24)
Main Parachute	2 grams Black Powder	Alt < 3000’, Pressure Increasing, V < 400 fps

The Raven only allows a single timer, so the Backup Apogee was configured to be the Sustainer Separation timer plus a 24-second delay, yielding a 38-second total time. The backup apogee charge was connected only to unit #1386.

One Raven (#1384) and one R-DAS (Designated ‘A’) were configured for the sustainer. The R-DAS was configured as the primary system.

Event	Charge	Trigger
Motor Ignition	M685W	Timer @17 s
Apogee	12 grams CO_2 (CD3)	Accelerometer-based Apogee
Main Parachute	2 grams Black Powder	3000’ AGL

The programming of the sustainer Raven is the result of a detailed failure mode effects analysis and designed to incorporate the Raven strictly as a backup to ensure a safe recovery. This configuration includes compromises to work around Raven programming limitations and the anticipated range of the barometer. We estimated that the Raven barometer would not be reliable beyond 110k’ MSL, while our simulations suggested a maximum altitude of over 125k’ MSL, so we needed to program the Raven in a manner that would tolerate an early false-detect of apogee.

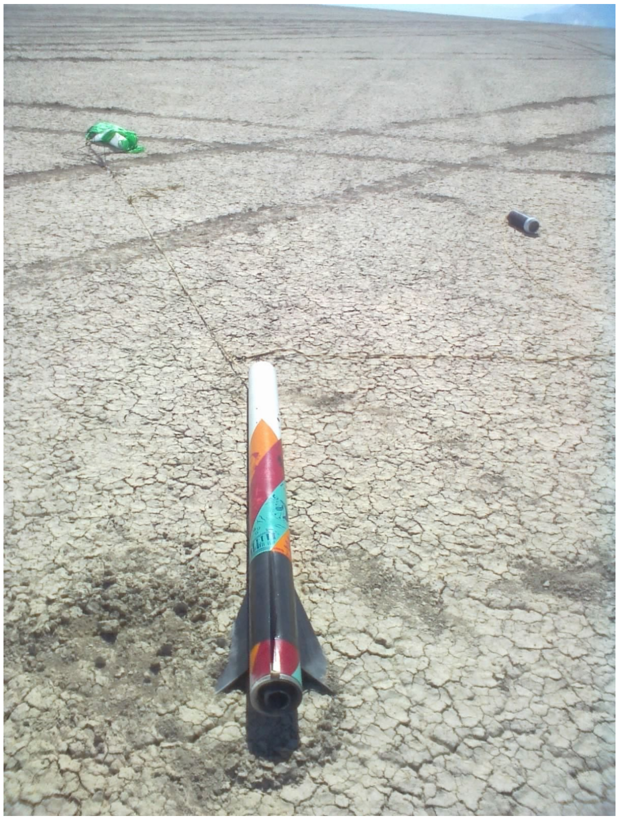
Event	Charge	Trigger
Apogee	12 grams CO_2 (CD3)	Pressure Increasing, V < 400 fps, Time < 51.5 s
Backup Apogee	2 grams Black Powder	Pressure Increasing, V < 0, +30 s delay
Main Parachute	2 grams Black Powder	Alt < 3000’, Pressure Increasing, V < 400 fps

The Apogee event is designed to safely recover from a total failure of the R-DAS, wherein the sustainer motor is not ignited. In this case, sustainer apogee would occur well within the Raven barometer's operational range. Beyond 51.5 seconds (the longest timer allowed on the Raven, and shortly after expected apogee without sustainer ignition), this event is disabled. From that point on, the Raven can only fire the backup apogee charge, and it does so on a long delay to overcome early detection of apogee due to the barometer exceeding its operational range. This event is meant as a backup should the R-DAS fail after sustainer ignition, or should the CD3 charge itself fail. In this kind of failure mode, apogee separation could occur extremely late, but we believed that the thin atmosphere would be more forgiving and less likely to destroy the airframe and parachutes at speed.

Flight Data

The rocket left the rail and immediately took on a substantial westward lean. There was none of the coning seen in the stack test. The sustainer ignited successfully.

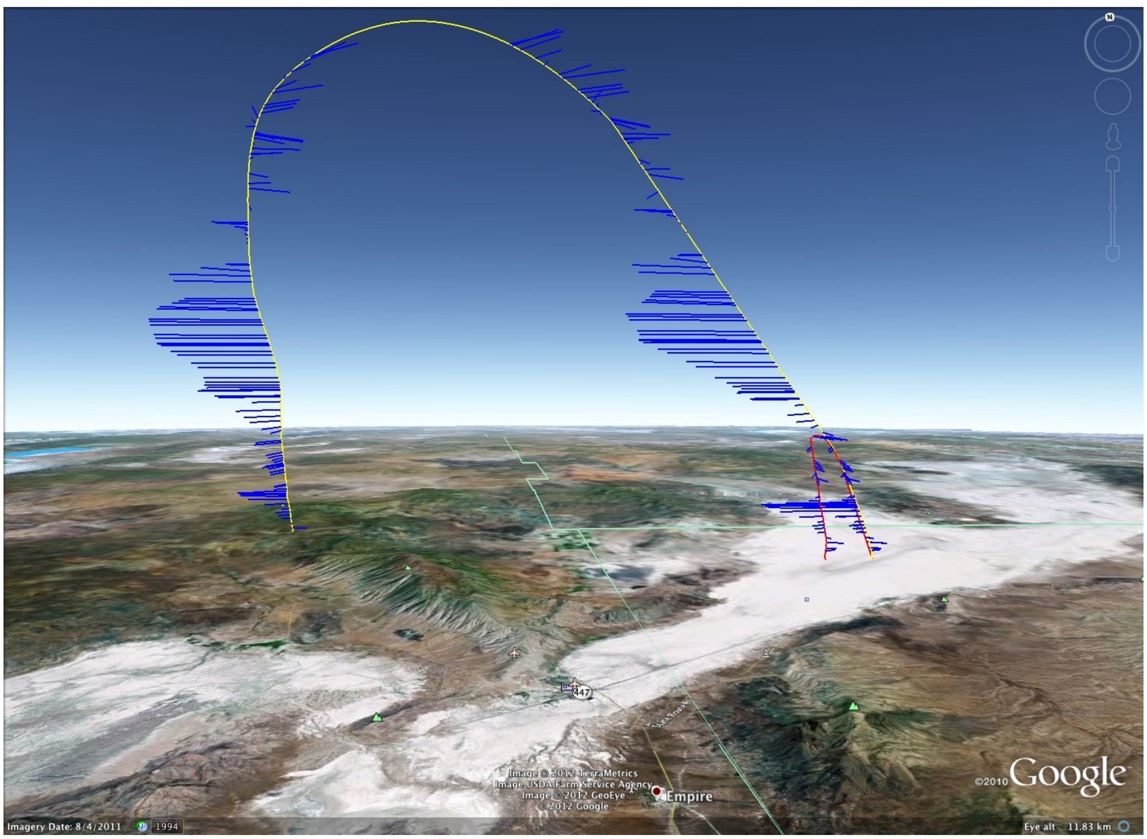
The booster was recovered 1.75 miles west of the launch site. All charges were blown. The booster was missing its upper rail guide. The rail guide was later recovered 30 feet from the launch rail.



Booster Recovery
Photo: Becky Green

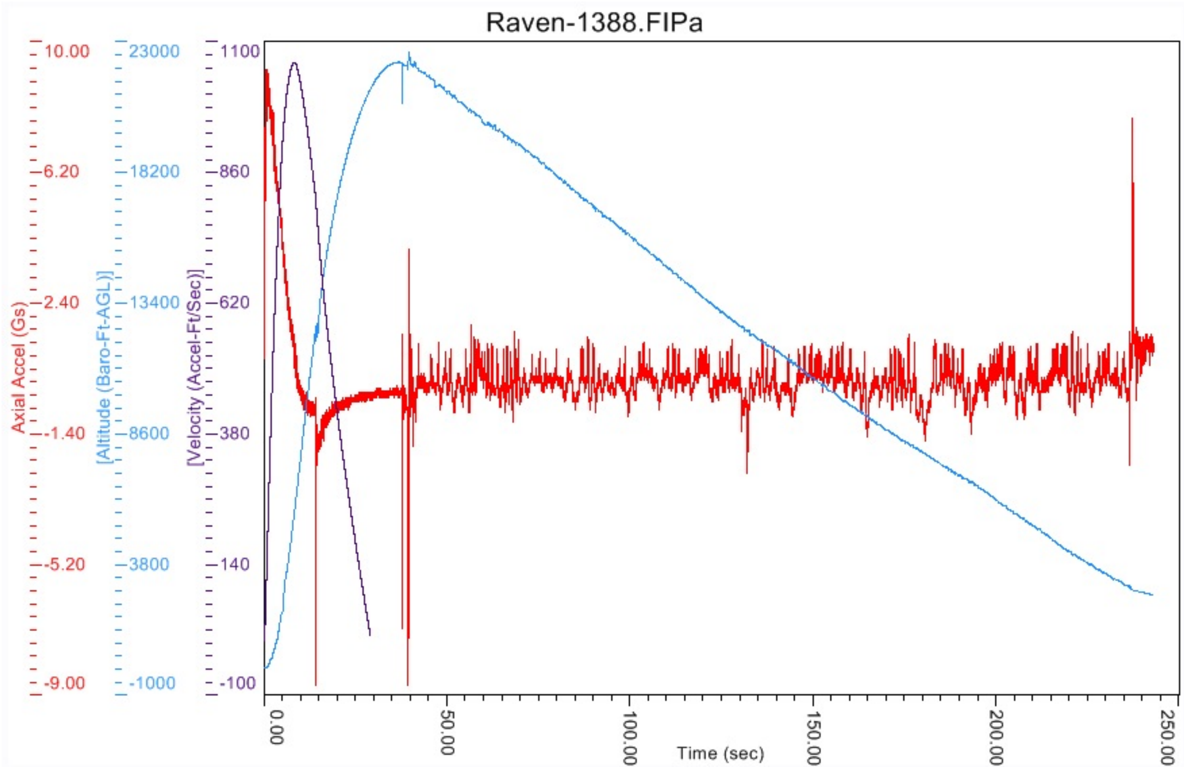
The recovery of the sustainer was based on last-heard beacons from the Beeline at ~500 feet AGL, just as it passed behind mountains. Within an hour, we assembled and dispatched a recovery team equipped with a 4WD vehicle. The team navigated over 100 miles by ground, much of it over difficult trails, to reach the last-known position. They recovered the sustainer 22 miles west of the launch site. All BP charges were blown, but the apogee CD3 canister was not pierced, despite a burnt e-match. The lower third of the airframe's paint was blistered. The recovery team returned to the launch site with the sustainer seven hours later.

Beeline GPS logs indicate that the rocket's angle from the pad was 16.9° from vertical at sustainer separation and 19.4° at sustainer ignition. Immediate (1-second average) trajectory was 25.7° at sustainer ignition. Sustainer apogee was 104,659 feet (31900 m) AGL at T+93 seconds, 40.8° off vertical and 17.1 miles downrange from the pad. At apogee, the sustainer was moving 1098 fps, accelerating to 1198 fps before the drogue ejected. Booster apogee occurred at 23,238 feet (7083 m) AGL.



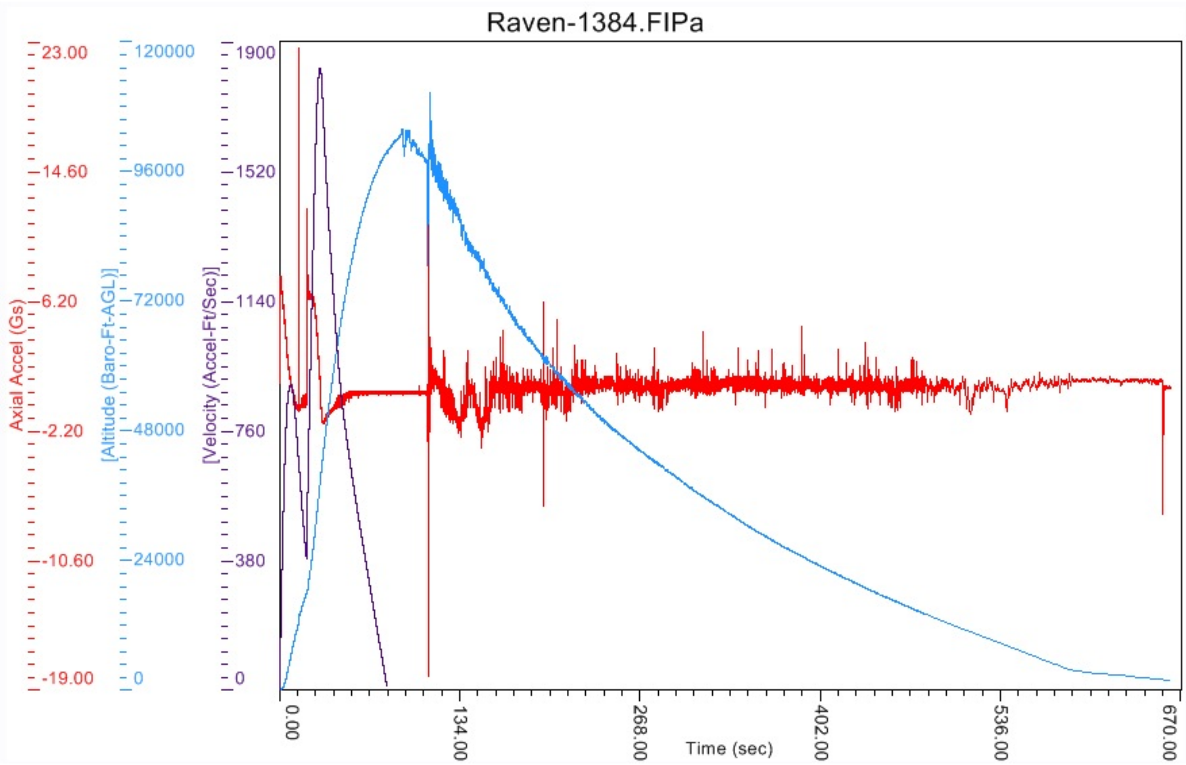
Full Flight 1 – GPS Tracking and Wind Overlay

Booster Raven #1388 recorded a nominal flight profile. (We inadvertently erased booster Raven #1386 while trying to download its data.) Booster apogee occurred at 37.5 seconds, which was slightly later than anticipated and close to the backup apogee timer.

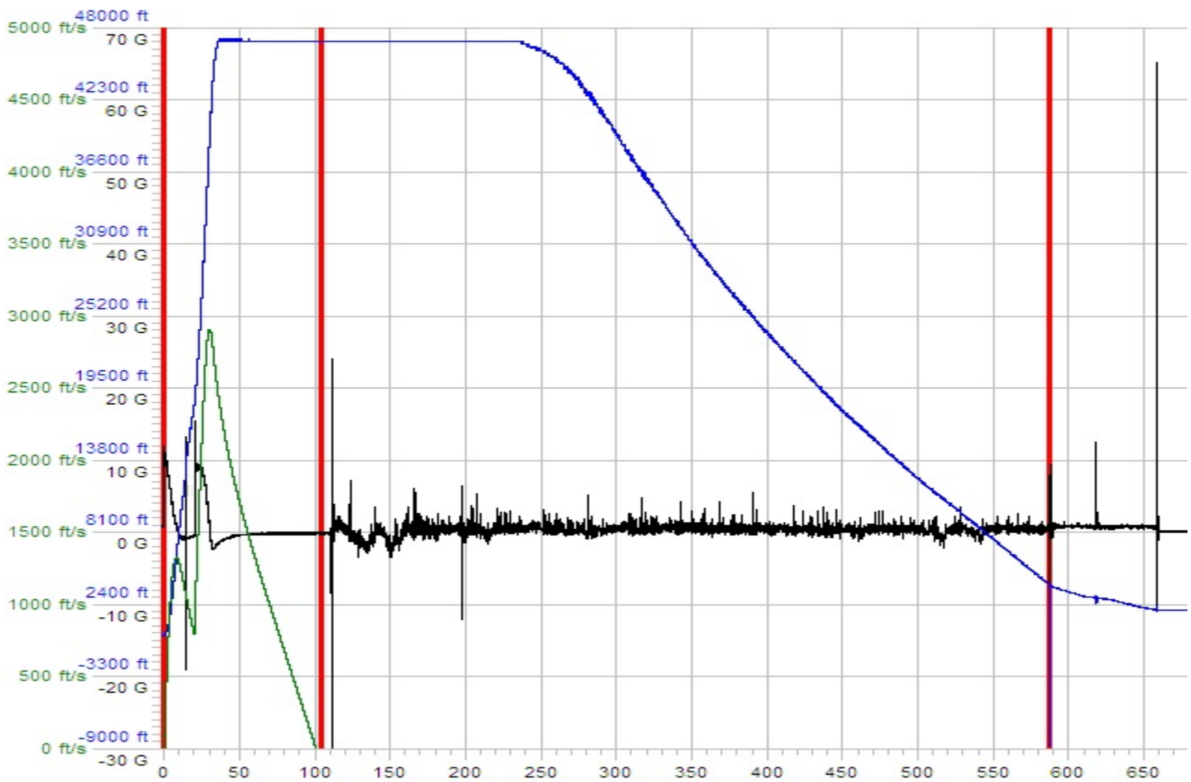


Full Flight 1 – Booster Raven

The sustainer R-DAS indicates that it attempted to fire the apogee CD3 at T+105 seconds, to no effect. At that point, the R-DAS barometer was pegged well beyond its operational range, but the GPS and the Raven barometer both indicate actual apogee occurred at T+93 seconds, 12 seconds earlier. Although the Raven's barometer data shows the apogee quite clearly, the trigger did false-detect apogee at T+80 seconds (99,483 feet AGL), seemingly due to noise in the barometric pressure. As the backup apogee event was configured for a 30-second delay, the Raven fired the BP charge at T+110 seconds. The data indicates this backup event is what deployed the nose cone and drogue. This is verified by the on-board video; the CD3 makes a muted "pop" noise, then the backup event ejects the nose cone.



Full Flight 1 – Sustainer Raven



Full Flight 1 – Sustainer R-DAS

The payload and booster GoPros both recorded full flight video, which we edited for distribution[41]. The videos show that roll rates were similar to the stack test flight, <2 Hz in either direction, with some back-and-forth rolling as velocity changed.

Video Frame near 104k' AGL, Looking Southwest

We found only modest impact from the high velocity flight on the booster. The full stack barely exceeded Mach 1, so we anticipated little damage due to speed or heating and we found none. The ISC, in particular, showed no signs of heating.

The 'A' ISC after three flights, including the 104k' AGL flight.
Photo: Ken Biba

[41] http://www.youtube.com/watch?v=1MVmH0bkMqE

However, the sustainer exceeded Mach 3, and we found evidence of that in the sustainer paint. The shape of the nosecone acted to separate the airflow from laminar flow over about half of the sustainer airframe, and the shockwave only really returned to the airframe about mid-way down. We can see this in paint bubbles caused by the heating, which created lovely “speed marks” across the spiral paint job. We saw no evidence of aerodynamic heating effects on the fins.

Paint Scars from Aerodynamic Heating
Photo: Erik Ebert

Sustainer Fins after Flight
Photo: Ken Biba

Analysis and Results

The exhausted but elated sustainer recovery team rolled into camp at approximately 9:30 pm, to wild cheers. Thanks to their heroic effort, the sustainer was recovered intact and well within the 24-hour limit required by the Carmack Prize. All of the data from altimeters, cameras, and GPS agrees that the flight broke the prize altitude.

> **Result:** We posted our claim for the Carmack Prize.

A careful dissection of the sustainer CD3 revealed nothing conclusive, but the BP in the piston did not burn completely, suggesting some kind of pressure leak. Fortunately, the Raven's programming as a backup system worked exactly as intended, the careful packing of the BP charge maintained enough pressure for it to detonate, and the thin atmosphere was as forgiving of late deployment as we had expected. Video suggests that the airframe was floundering when the nose cone and drogue deployed, so it's likely that it would have survived an even longer delay to deployment. Even at 1198 fps, the air density was too low for the drogue to damage the airframe.

> **Result:** We inspected our remaining CD3 charges for leaks and reapplied RTV to further seal the e-matches.

The Raven false-detected apogee just below 100k' AGL, or about 104K' MSL. Our 30-second delay for backup apogee was premised on false-detect happening closer to 110K' MSL. If 104K' MSL represents a hard limit for the Raven, then 30 seconds is likely too short for a fully vertical flight. However, the trigger occurred when the trajectory was 69° off-vertical, meaning the barometer was sensing about one-third of the net velocity. Had the flight been straighter and higher, we think the Raven's false-detect, while inevitable, might have occurred closer to our original estimate. Also, we expected slightly less performance from the CTI motors planned for the following flights. So in short, we decided it was probably a wash, and that 30 seconds was OK. And in any event, the backup event saved this flight, justifying our decision to keep it.

> **Result:** We kept the Raven's apogee and backup apogee trigger programming for the following flights.

The sustainer came down 22 miles away, on the far side of mountains that peaked 5,000+ feet above the launch site. We noted that, had it landed near a peak, the main would not have deployed in time.

> **Result:** Changed sustainer Raven and R-DAS to deploy at 6,000 feet AGL. Booster unchanged.

Video suggests that the stack took on a lean even before leaving the rail, so we attributed the strong lean in the flight path to the broken rail guide.

Result: Removed the remaining conformal rail guides. Replaced them with large buttons screwed into the booster av-bay bulkhead and the aft closure of the booster motor.

The booster's apogee (37.5 seconds) was very close to the backup apogee timer (38 seconds), despite the off-vertical trajectory.

Result: We advanced the booster backup apogee timer to 39 seconds.

4.4 ARLISS/XPRS Full Flight 2

We conducted a full mission flight of Airframe A at the AeroPac *ARLISS* launch at Black Rock on September 13, 2012, two days after the same airframe reached 104k'.

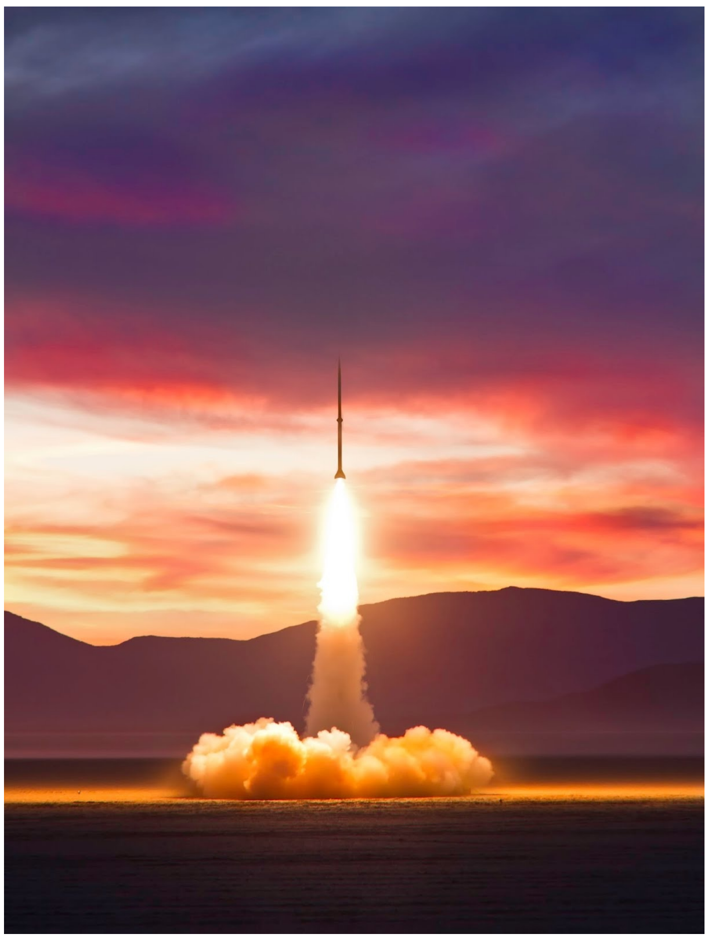


Photo: Tom Rouse

Configuration

This flight used a full complement of motors. However, AeroTech did not have additional M685 motors available, so we used the reserved CTI motor in the sustainer.

- A 6-grain 75mm CTI M840 was used in the sustainer.
- A 6-grain 98mm AeroTech N1000W was used in the booster.

The recovery systems were identical to the first flight. The payload was again replaced by ballast weight.

The avionics configuration was similar to the first flight, except that the booster's backup apogee was moved to 39 seconds and the sustainer's main parachute deployment was moved to 6000', as discussed in the results from the prior flight.

The rail guides on the booster were replaced with the screw-mounted buttons, as described in the results from the prior flight.

Having packed the airframe and elevated it on the launch rail, we discovered that the sustainer R-DAS had lost continuity to at least one of its charges. Unfortunately, the beep pattern of the R-DAS does not indicate which channel is failing, so we removed the stack from the rail and dismantled it. We discovered that a sustainer motor ignition wire was broken, likely caused by repeated insertions while getting the sustainer av-bay aligned with the airframe.

We finished repacking the sustainer shortly before sunset, so pad loading was somewhat rushed. This being the second time out to the pad, we overlooked a checklist item and failed to enable the on-board cameras before the flight. At the pad, we noted that the sustainer Raven had now lost continuity to the apogee CD3, but as the Raven's control of the CD3 was strictly a low-altitude backup, we decided to fly anyhow.

Flight Data

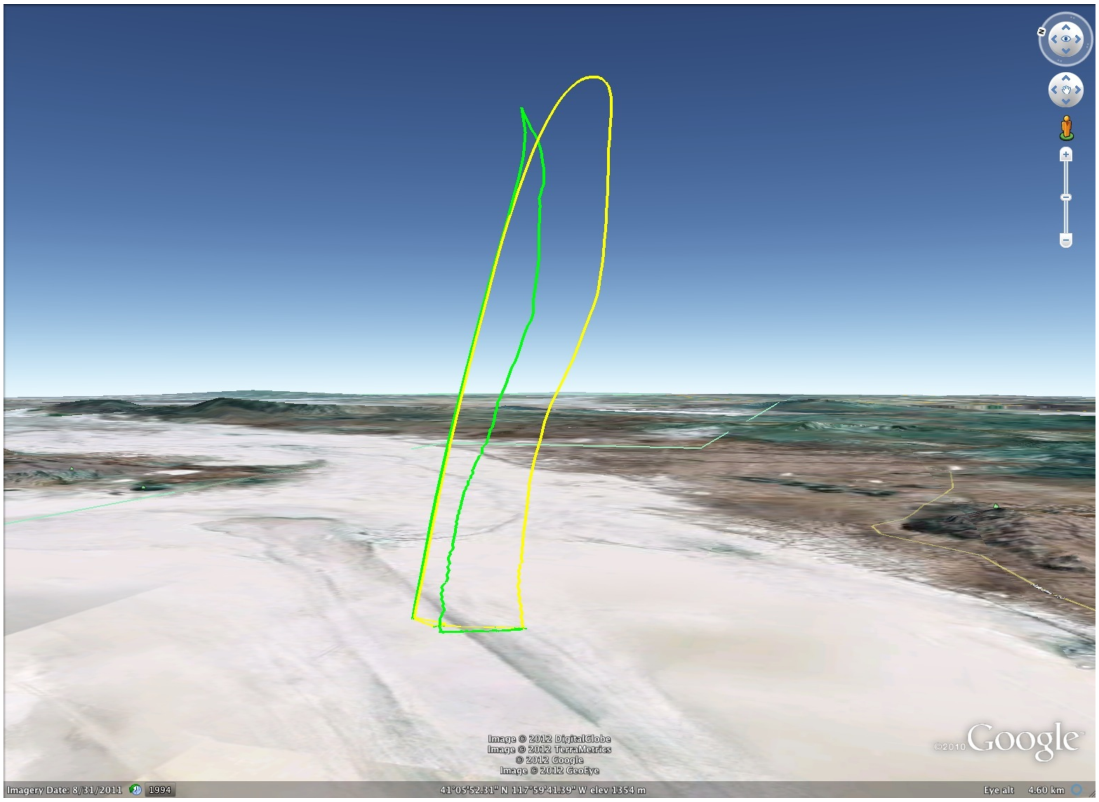
The flight left the rail with a modest southward lean, seeming to pull away from the rail, but the lean was not as steep as the first flight. The sustainer motor lit on schedule, but the flight did not appear normal. The bright orange trail made some of us suspect that the sustainer motor had somehow failed. However, telephoto images of the staging event later revealed that the sustainer was corkscrewing severely.

Photo: Pat Wagner

The booster was recovered 1.0 mile due south of the launch site. All charges were blown.

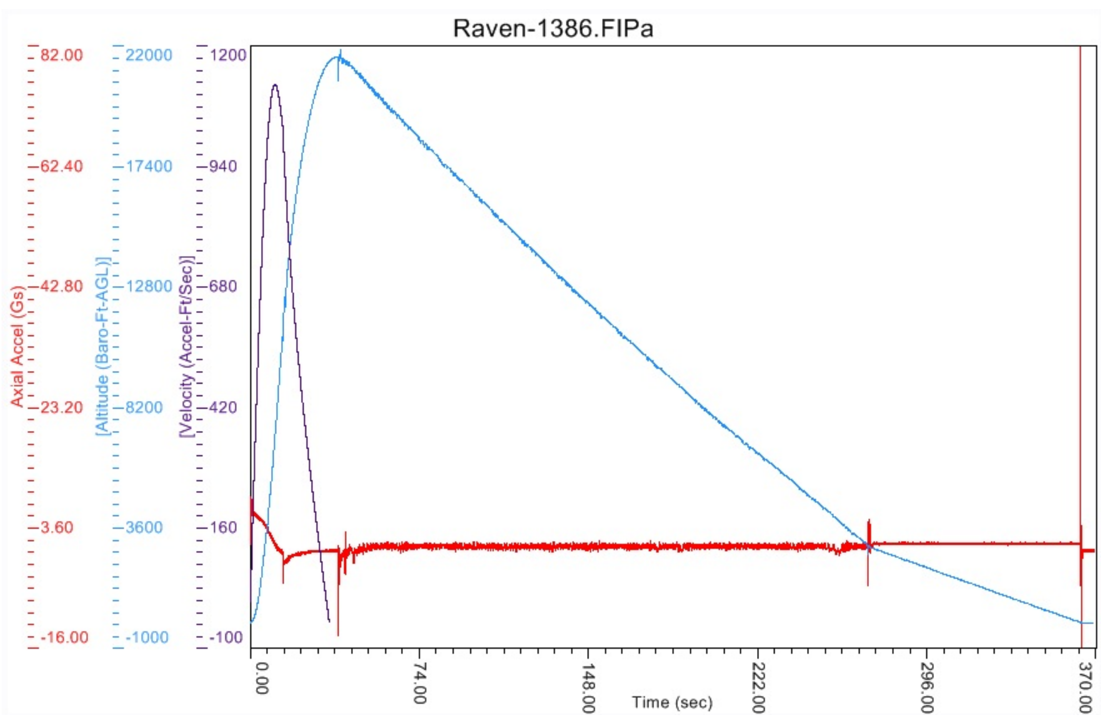
The sustainer was recovered 0.5 mile southwest of the launch site. The nose cone shock cord was broken and the nose cone was found near the sustainer. The drogue's shroud lines were mostly torn away, but it provided enough drag to save the nose cone from a purely ballistic return. The nose cone CD3 was not blown, but all other charges were.

GPS logs indicate that the rocket's angle from the pad was 13.5° off vertical at sustainer separation. Sustainer apogee was 21,850 feet (7840 m) AGL at T+27 seconds, 13.8° off vertical and 1.0 mile downrange from the pad. Booster apogee occurred at 22,847 feet (6964 m) AGL, slightly higher than the sustainer.



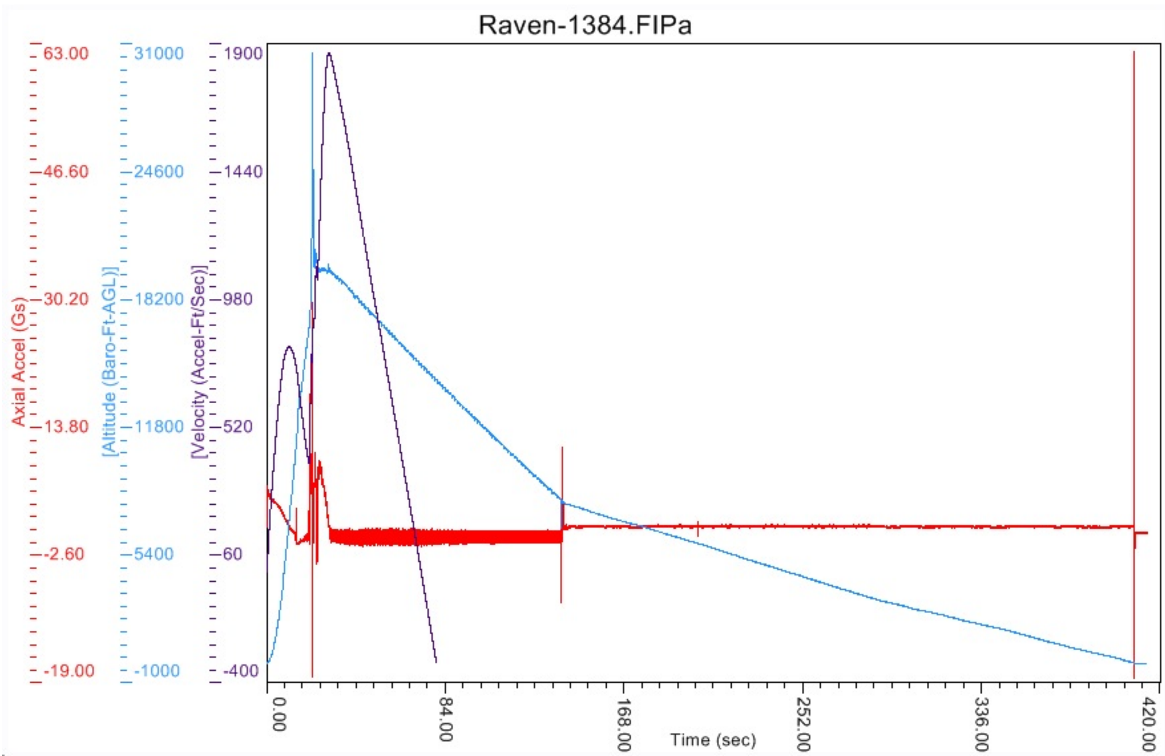
Full Flight 2 – GPS Tracking

The booster Ravens both recorded a nominal flight profile.

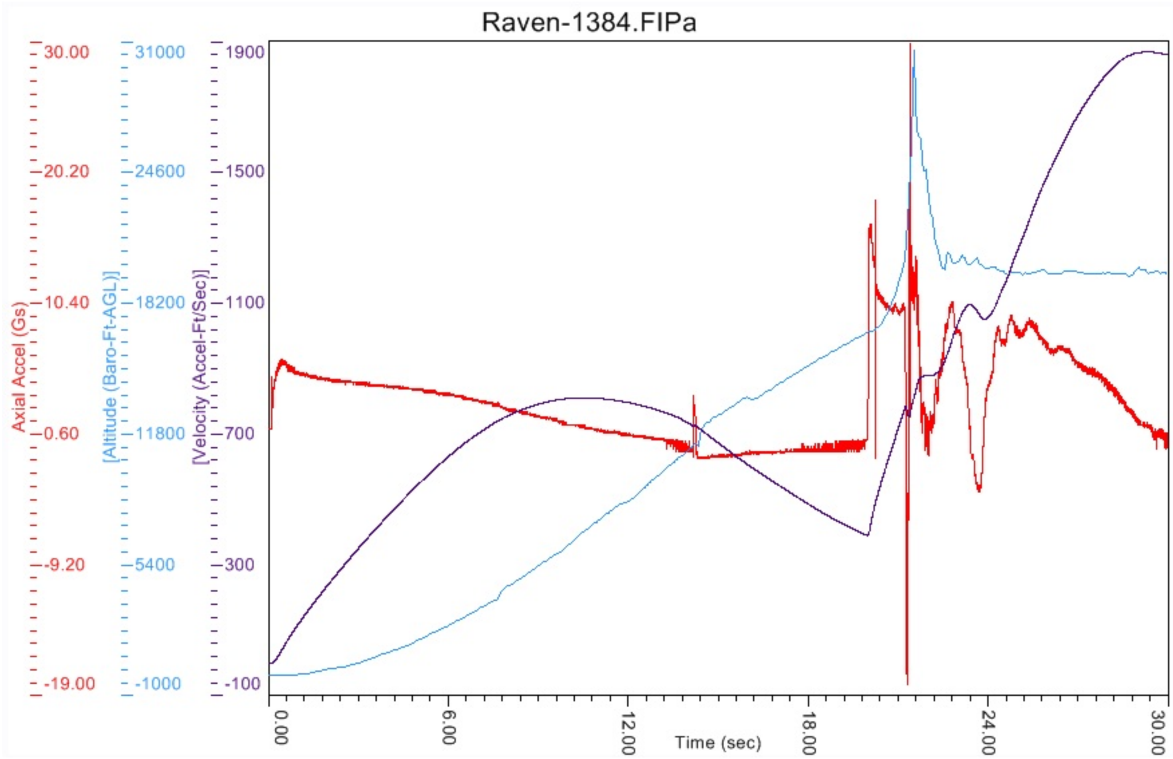


Full Flight 2 – Booster Raven

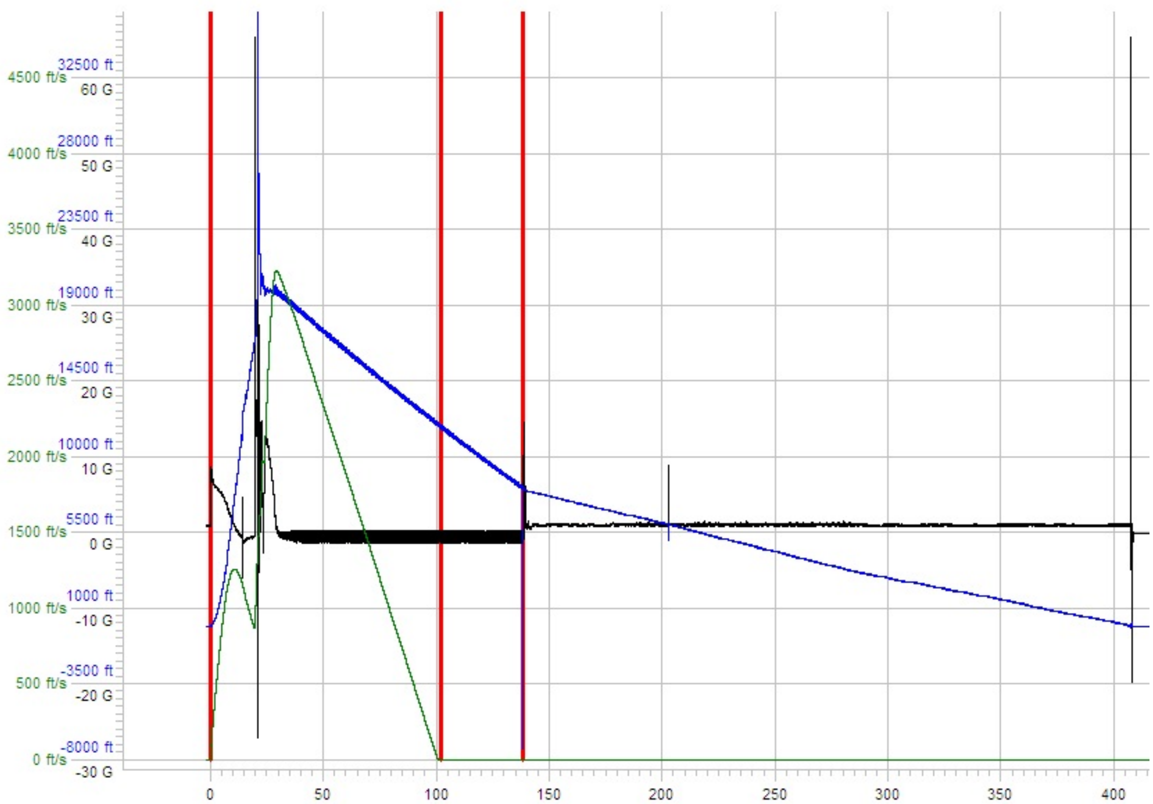
Unlike previous flights, the sustainer Raven's *lateral* accelerometer showed a 5-Hz oscillation approximately 1 G in magnitude beginning immediately after separation, suggesting the corkscrew began *even before* sustainer ignition. Both the Raven and R-DAS recorded significant turmoil following ignition, with large axial and lateral transition swings of up to 50 G in magnitude.



Full Flight 2 – Sustainer Raven



Full Flight 2 – Sustainer Raven (Zoom to Boost Phase)



Full Flight 2 – Sustainer R-DAS

Barometric data shows wild pressure fluctuations during the sustainer burn, but suggests that apogee occurred at approximately T+30 (+/- 5) seconds, which agrees with the GPS apogee at T+27 seconds. However, because of the strained flight profile, the R-DAS single-axis accelerometer did not trigger the apogee event until 102 seconds, as indicated by the vertical red line. Further, as noted at launch, the Raven had lost continuity to the apogee CD3 charge on the pad, so its baro-based programming could not fire the apogee CD3. Because of the long delay on the Raven's backup apogee BP charge, it did not fire until 110 seconds.

> *Esoteric details: The sustainer Raven's backup apogee charge was configured with the accelerometer-based Mach lock-out to protect against early baro detection, but for this event only, we decided to extend the lock-out until the Raven's accelerometer actually detected apogee, or velocity=0, since that had always occurred well in advance of real apogee, and we thought the longer lock-out might be beneficial if the barometer encountered noise. This approach worked fine on the first flight, but on this flight, the Raven's axial accelerometer suffered the same integration issue as did the R-DAS, causing it to not release the event lock-out until 80 seconds, well past when the barometer detected the real apogee. That, plus the 30-second delay, yielded the backup apogee event at 110 seconds. Our longer lock-out makes the backup charge far too late to help in early-abort flights. However, had the CD3 kept continuity, the Raven's barometer would have fired it on time.*

Fortunately(?), none of the apogee events turned out to matter, because as the data hints, we believe the sustainer was flying sans-nose cone, and well into a floundering descent at around 100 fps by the time either apogee event was triggered. If the Raven had established continuity to the nose cone's apogee CD3, we would have a record of the disconnection time, but that wiring harness was broken during recovery packing. Unfortunately, the R-DAS does not record channel continuity.

Oddly, the R-DAS fired the main parachute charge at 138 seconds while the sustainer body was still descending at around 8000 feet, or about 2000 feet before it was intended. This deployed the main parachute earlier than desired, but as there was little wind, the landing was still nearby. We have no explanation for this discrepancy.

Analysis and Results

Immediately after the flight, before recovering the data or any of the imagery, we speculated about the bright orange fireball we saw at sustainer ignition. From the ground, it seemed as if the CTI motor had failed.

> **Result:** Although we had no hard data, we began to seek out and prepare an AeroTech motor for the next flight, in place of the CTI M840.

Once recovered and analyzed, the data suggested that the sustainer airframe was in a bad configuration before the sustainer motor fired. We suspect that, in our rush to re-pack the airframe, the sustainer's recovery bay was too tight against the nose cone, and that this caused extra stress on the nose cone shear pins. This tight packing also broke the wiring harness from the Raven to the apogee CD3. When the sustainer separated from the booster, we speculate that the nose cone drag-separated from the shock, or at least cracked the shear pins and cocked at an angle. The stage separation shock masks any anomalous accelerations, except for the continuing lateral oscillation, and it's not clear whether the nose cone was still attached to the sustainer when the motor lit. It might have been loose or nearly out. The first large lateral/axial spike occurs 0.3 second after motor ignition, so that might be the nose cone separating or breaking the shock cord.

> **Result:** Decided against changing the shear pin configuration for now, but made sure to pack the next flight more carefully.

The rushed schedule was triggered initially by the loss of continuity to the sustainer motor, which we did not discover until we had gone as far as loading the stack onto the pad. Had we tested the sustainer electronics on the ground immediately after packing, we would have saved considerable time. However, the skittish nature of the magnetic switches, coupled with the sustainer's ability to light its own motor, gave us concerns about powering up avionics in camp. The Raven does not beep out its continuity unless it is powered up vertically, which arms it. The R-DAS does not beep out specific channels and is always armed at power-up.

> **Result:** Carefully ground-checked R-DAS continuity on the next flight while still in camp. Did not check Raven continuity.

The flight's boost phase was measurably improved in verticality. We think a nominal sustainer trajectory would have gone higher and landed closer than Flight 1, but it was still somewhat off-vertical. We noted that this flight tilted away from the rail, which led us to think perhaps it was leaning away when the top button left the rail.

> **Result:** Tilted the next flight toward the rail slightly.
> **Result:** Shortened the sustainer ignition delay.

4.5 ARLISS/XPRS Full Flight 3

We conducted a full mission flight of Airframe B at the AeroPac *ARLISS* launch at Black Rock on September 16, 2012.

David Raimondi, Tom Rouse, Jim Green, Casey Barker, Becky Green, Erik Ebert & Pumpkin
(Ken Biba and Steve Wigfield not shown)
Photo: Melanie Barker

Configuration

This flight used *nearly* the full complement of motors. As noted in the Flight 2 results, we opted to prepare an AeroTech motor for the sustainer because we were not sure the CTI motor had worked properly. As there were no 6-grain 75mm AeroTech motors available, we located a 5-grain long-burn motor at [Bay Area Rocketry](http://bayarearocketry.com)[42] and borrowed a casing from [What's Up Hobbies](http://www.whatsuphobby.com)[43]. (Many thanks to our vendors for their on-site assistance.)

- A 5-grain 75mm AeroTech M650 was used in the sustainer.
- A 6-grain 98mm AeroTech N1000W was used in the booster.
- The shorter sustainer motor necessitated a small extension rod to connect the av-bay.

As this was the first ever flight of Airframe B, including all the on-board components, there were more than the usual number of last-minute assembly glitches. We also had to replace the rail

[42] http://bayarearocketry.com
[43] http://www.whatsuphobby.com

guides, as we had done on Airframe A. This slightly delayed preparation, and we missed our window of calm morning air on September 15. We bumped the flight to September 16, which was the last day of the launch.

The rescheduling required that we dismantle the airframe so we could charge the GoPro cameras, which had been running on the WiFi Bacpacs. In the process, we noted that we could access the sustainer camera by removing the nose cone from the shoulder, avoiding one repacking process. Desiring to fly early in the morning, we removed the GoPro WiFi Bacpacs and simply drilled holes in the airframes to access the GoPro power switches directly. We reconfigured the GoPros for one-button operation, replaced their batteries, and re-packed the airframes. This allowed us to button up both airframes the night before the launch without worrying about parasitic current.

The recovery systems were similar to those of Airframe A. The Nexus payload was installed in the sustainer for this flight.

The avionics configuration was the same as on the second attempt, except we moved the sustainer ignition to 15 seconds, 1 second past the stage separation event, hoping to light the sustainer while it was as vertical as possible.

As we loaded the stack on the rail, we found that the booster ISC had gotten cold overnight and was too tight to fit the sustainer motor. We heated the ISC with a car heater until it loosened up enough to fit the motor.

Once it was stacked on the rail, we discovered that one of the grains in the epoxied N1000 motor was misaligned, so we could not insert the igniter past the first grain. Thanks to James Dougherty (demonstrating a camaraderie representative of AeroPac members), we acquired a donor N1000, and quickly set to work cutting out the misaligned grain and epoxying a new one. Fortunately, the epoxy cured before launch closed down. While we waited, we enlarged the protective channel in the ISC to ensure that stage separation would not break the copper tape to the sustainer igniter.

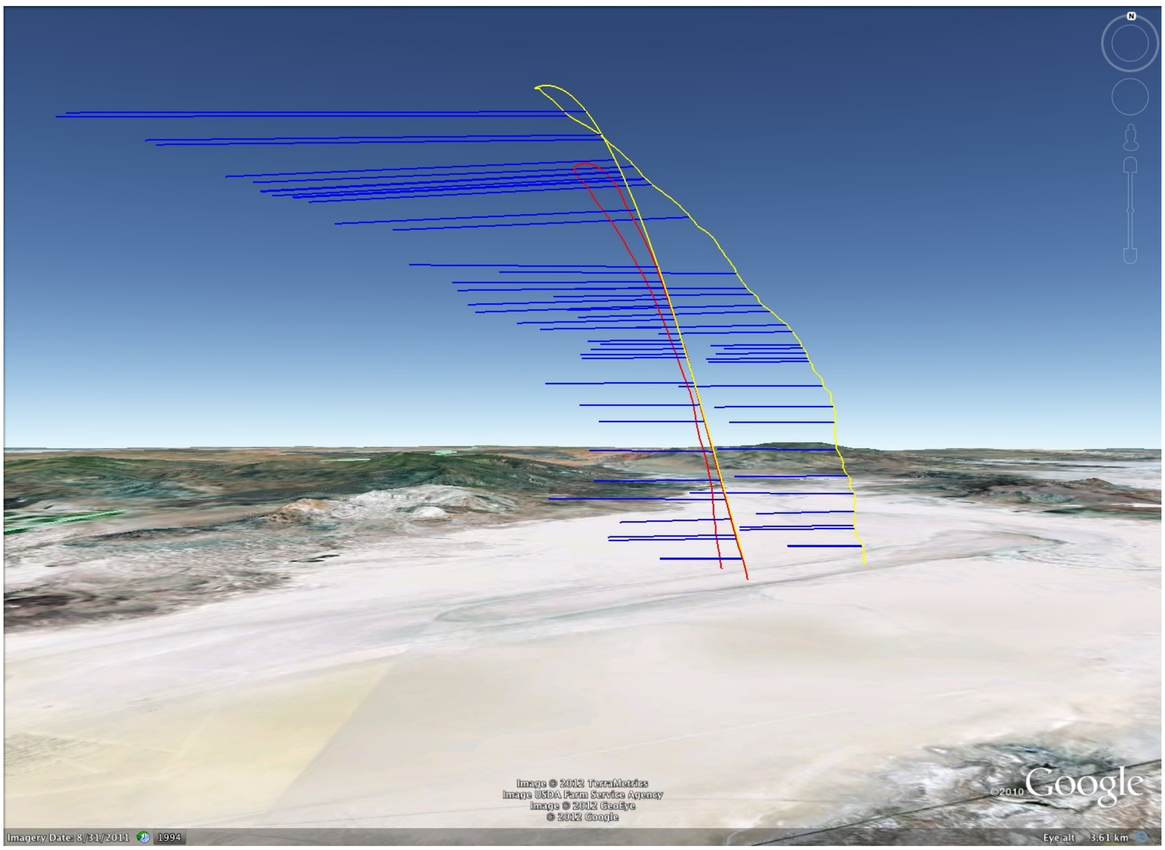
Flight Data

The flight left the rail with a moderate westward lean, not as steep as the first flight, but in the same direction. Ground winds were higher than previous flights, and out of the west, suggesting that the stack might have weathercocked. The sustainer motor did not light. The booster returned normally, but never opened the main parachute. The sustainer return was very slow.

We recovered the booster 0.75 mile north of the launch site. All charges were blown, but the airframe was heavily “zippered” and the ISC shock cord trapped in the fiberglass. This locked the main parachute into the body, so it did not deploy. The resulting impact cracked one fin loose from the body tube. The ISC staging piston was detached from its tether and broken, but we noted that we had forgotten to drill vent holes in this one.

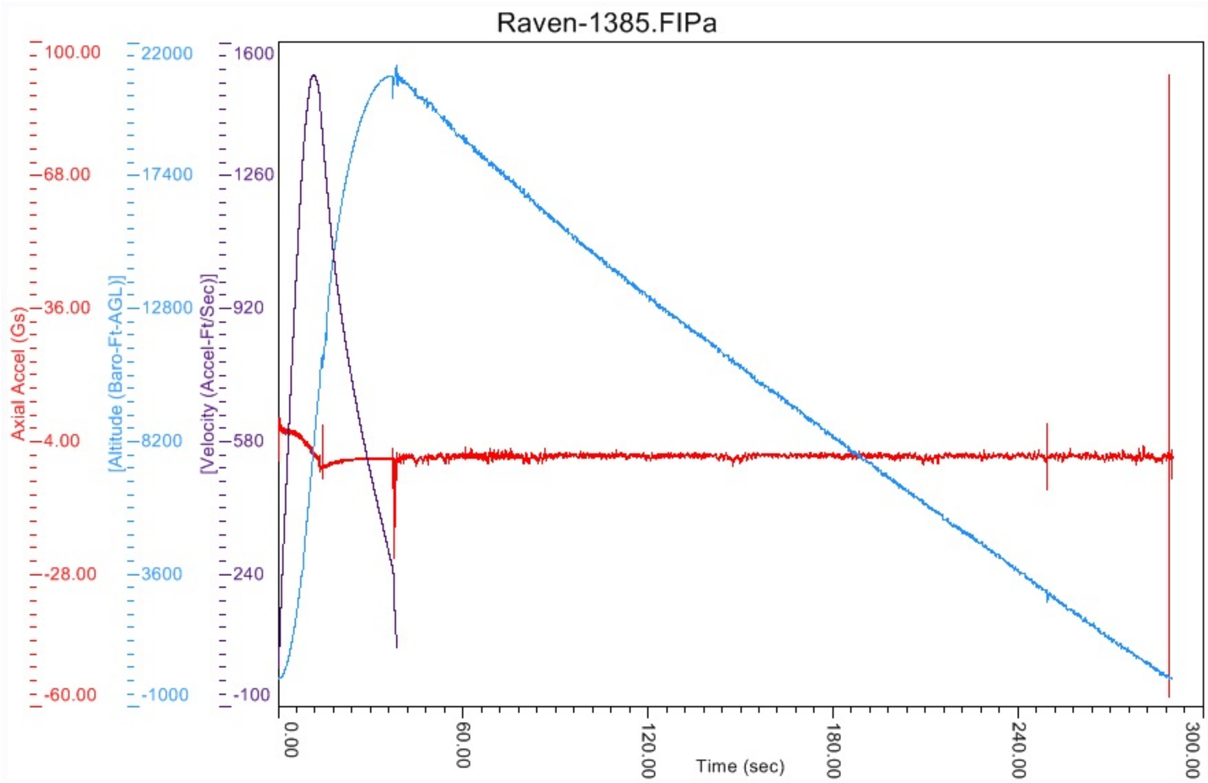
We recovered the sustainer 1.9 miles northeast of the launch site. The nose cone shock cord was broken, and we found the nose cone near the sustainer. The sustainer was also heavily zippered and the main parachute's center-pull shroud line was ripped out. The motor igniter wire was cleanly cut.

GPS logs indicate that the rocket's angle from the pad was 15.0° from vertical at sustainer separation. Sustainer apogee was 25,879 feet (9077 m) AGL at T+48 seconds, 23.1° off vertical and 2.1 miles downrange from the pad. Booster apogee occurred at 21,732 feet (6624 m) AGL. The blue lines in the GPS map show the wind speed and direction at various altitudes as determined from NOAA data.



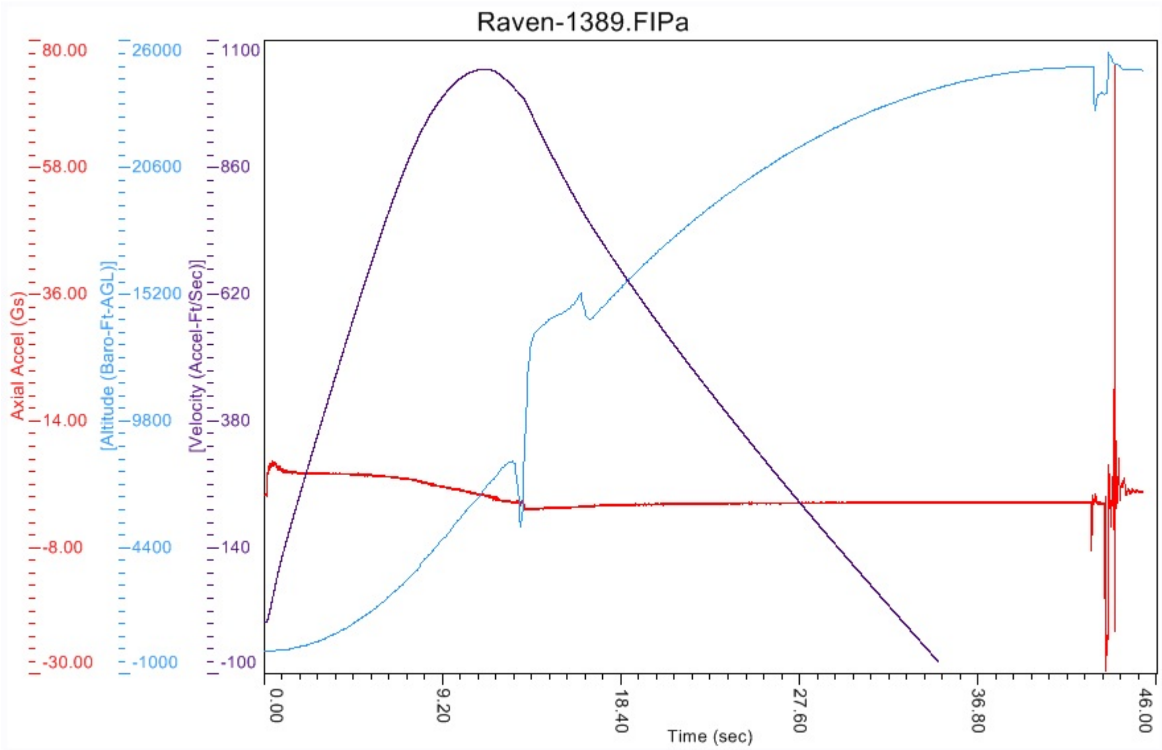
Full Flight 3 – GPS Tracking and Wind Overlay

The booster Ravens recorded a nominal flight up to ISC ejection. About a half-second past ejection, axial acceleration peaked at 25 G and lateral acceleration at 47 G. (Prior flights showed 10-15 G.) There was no deceleration from the main parachute ejection event, and the booster struck ground at ~80 fps.



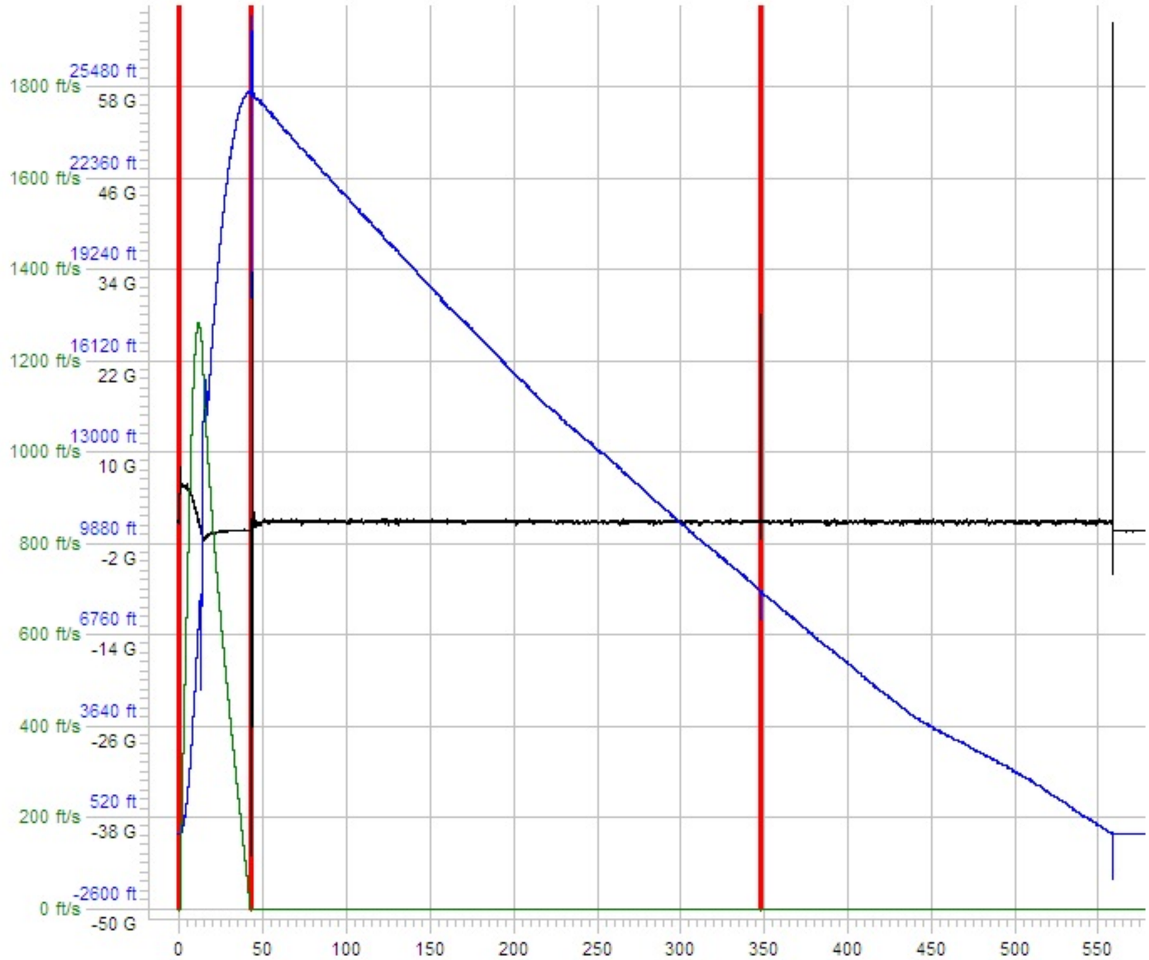
Full Flight 3 – Booster Raven

The sustainer Raven recorded a nominal flight, minus the sustainer boost, up to nose cone ejection. The Raven data log indicates that the R-DAS actually fired the apogee event, as it lost continuity to the apogee CD3 just before it would have detected barometric apogee, and this validates the R-DAS fired very close to real apogee. Acceleration data around the ejection is modest, but nearly a second after ejection, axial acceleration peaked at 76 G and lateral acceleration peaked at 41 G. At this shock, the Raven recorded a drop in battery voltage, suggesting that the battery had been disconnected. The Raven, running on the capacitor, stopped recording 2 seconds later.



Full Flight 3 – Sustainer Raven

The sustainer R-DAS data agrees with the Raven up to the point where the Raven stopped recording. Past apogee, the descent rate is slow, indicating that the main parachute was deployed at apogee. Video from the sustainer nose cone camera confirms this. The sustainer and main parachute are clearly visible from the nose cone as it falls away separately on the drogue.



Full Flight 3 – Sustainer R-DAS

On-board video shows that roll rates were very low, with only a minor back-and-forth wobble until separation, at which point the sustainer and booster rolled lightly in opposite directions.

Analysis and Results

We do not completely understand all of the issues on this flight, but we can tease out some answers.

Airframe zippers and broken shroud lines typically suggest that velocity is too high at the time of deployment, but the GPS tracks show that the booster and sustainer pre-apogee velocities were no higher than any of the prior flights. However, at apogee deployment, both exhibited a sudden change of direction down-wind. Unlike the test flight regime, the boosters in full flights experience apogee deployment in the middle of the jet stream, as do sustainers in the event of an ignition failure. Wind data from the day suggests those layers averaged 40 knots (blue lines in the GPS track image), much higher than all previous flights. We believe that strong gusts combined with weathercocking at apogee to result in very high *relative* airspeeds, despite relatively slow *ground* speeds.

Flight videos and the state of the airframes at recovery suggest that, on both the booster and sustainer, the drogue chutes whipped the airframes around and zippered them. On the sustainer, the whip acted to fling the main parachute out at apogee, breaking the shroud and imparting the larger secondary acceleration spike. On the booster, it pinned in the main parachute.

The failure to light the sustainer is not fully understood. The igniter wire was left slightly longer than in other flights, and it was coiled outside the nozzle cap during prep. It seems most likely that the ISC piston (which has a cutout to protect the copper tape to the igniter) caught part of the coiled wire against the aft closure, cutting it at stage separation. However, the cut wire could also have been caused by ground impact, as the aft closure struck hard rock. A post-mortem of the motor showed that the copper thermite was loose inside the motor, so it's also possible that the bag was pierced by the contact of the insertion dowel and piston, and that the e-match fired, but failed to light it. We lost the e-match during the post-mortem, so we don't know whether it was fired or not. The R-DAS's lack of continuity data further obscures the problem.

The verticality of this flight was again improved over Flight 1, and on par with Flight 2. However, even modest tilts can sacrifice altitude and complicate recovery when the target altitude is 100,000 feet, so some improvement is needed.

4.6 Celebration Flyover

During the launch, we were visited by a pair of F-15s at about 1000' AGL, and treated to a nice flash of afterburner.

Photo: Ken Adams

5.0 Lessons Learned

Although the system met the goals we set out to achieve, we learned many lessons along the way.

Some of these findings are still the subjects of heated debates. In some cases, our results became the fodder that renewed old debates. However, other aspects are more clearly agreed, and we have many concrete ideas to improve the system going forward.

The System Works

This system demonstrated conclusively that the basic concept of a two-stage stack with long-burn motors *works*, and can reach very high altitudes on remarkably little impulse. We believe this basic design can be extended to scale up to bigger motors for even higher altitudes. On its own, we hope this lesson will encourage others to attempt such designs and thereby advance the state of amateur rocketry.

Going Straighter

The single biggest challenge of the slow, long-burn approach is maintaining verticality over the course of the burn. We understood this at the outset, but having deeply internalized the lesson, we think we can improve reliability, recoverability, and performance by improving verticality. We think some combination of reduced gross weight, a higher-initial-impulse booster, and a longer launch rail would provide more velocity off the rail and help compensate for the weathercocking and off-vertical trajectory we encountered. This aspect will be the biggest focus of our efforts going forward.

Avionics

We learned a great deal about the strengths and limitations of the flight computers we used in this project.

Barometers, when coupled with a sensible Mach lock-out, can be a reliable means of detecting apogee below 100k’ MSL, and they are resilient in the face of abnormal trajectories. However, we’re convinced that for flights to higher altitudes, accelerometer-based apogee triggers are really the only way to go. This necessitates an accurate, high-resolution, high-rate accelerometer and a well-tested integration algorithm. (Perhaps the best all-around solution would be a hybrid approach, incorporating data from both?)

We found that our flight profile exceeded the design limitations of some systems. For example, some of our desired triggers for backup events exceeded the longest possible timers and highest possible altitude values. We did find that, although fully customizable compound-event triggers add complexity, they at least allowed us to creatively work around some of these limitations. Still, we would prefer just having higher limits.

Small is a virtue. We had issues fiddling with tiny wire terminals and breakouts, but we'd rather work around those issues than increase the size of the airframe.

Avionics-controlled motor ignition, as required for two-stage rockets, poses safety challenges. We think it should be easier to verify continuity through the enabled channels of a given unit, without fully arming it, and without changing orientations on the bench. The Raven will not arm when horizontal, but it also doesn't verify continuity in that configuration. To check continuity, the rocket must be lifted vertically, thus arming it. The R-DAS always provides continuity information, but it is *always* armed, which poses its own safety concerns. We don't have an easy answer for this. (In fact, it's a point of debate.) We will look to device vendors to come up with creative solutions in the future.

When armed at the pad, it should be easy to mask or ignore warnings from disabled channels. When everything is fine, the unit should make that obvious. When something's wrong, it should be easy to figure out exactly which channel is bad. When conducting post-mortem analyses, we found continuity and voltage level data, overlaid on the sensor data, to be *absolutely invaluable*. That information was the key to solving a number of otherwise-inexplicable riddles, and where it was missing, we have unsolved mysteries.

All our units offered some form of data visualization after download. This is very convenient for quick post-mortems in the field. But especially on anomalous flights, we wished for better export options so we could analyze data with more powerful tools, like spreadsheets.

In summary, we found each unit to have its strong points, and found ourselves wanting a "best of all worlds" unit. These are the features we found especially valuable:

Raven:

- High-range barometer
- Small and inexpensive, and works with tiny, low-voltage cells
- Initial orientation arms the device, inert when horizontal
- Supports complex triggers with delays, especially useful for backup events
- Beeps and records both individual channel continuity and battery voltage
- Giant capacitor buffers loss of battery voltage

R-DAS:

- Dependable accelerometer integration for apogee, necessary for high altitude
- Configuration is a model of simplicity, "it just works"
- High limits for configurable timers
- No unexplained data losses

Our Wish List:

- Ability to check continuity away from the pad, without arming
- Improved data export options

- Three-axis accelerometer, gyroscope, and magnetometer for full IMU-like data
- Tight integration with a modern (u-blox) GPS would be nice

We hope to take these lessons back to device designers to see if any of them can be incorporated into the next generation of flight computers.

Avionics Bay Layout and Design

We found that we preferred batteries that could disconnect and charge without being removed from the system. These were just far easier to deal with. Also, locking wire connectors have less inertia than do battery cells, so they are less likely to dislodge under heavy shocks. We'll look for ways to incorporate these lessons in new av-bays. (We may use the same cells, but with wire harnesses instead.)

In future designs, we will add hard-wired igniter terminals outside the bay, rather than breakout boards inside the bay. This makes it easier to deal with the small size of modern avionics, and we'd prefer to avoid re-RTV'ing wire bundles at bay entry points on every recycle of the airframe.

We will also consider how to pull umbilical cables outside the packed airframe for easy charging and configuration of avionics, cameras, etc.

Switches

In the field, we found it maddeningly difficult to power up and down individual components using magnetic switches when several were closely packed into the same bay, especially when the units emitted similar beep patterns, and doubly so when the units had large capacitors that made it hard to tell if the unit was really off. Going forward, we will prefer power switches that offer positive feedback as to whether a specific device is on, at least where there are multiple units in the same vicinity.

After a few accidental activations, we instituted a safety protocol so that magnets (and even magnetic tools) were kept a safe distance away from live rockets. In the field, we found it useful to designate one person the "magnet holder," and possession of the magnet required the person to keep a safe distance from the rockets.

Further, although we had conducted bench tests and determined that the parasitic loads were minimal, we felt a persistent concern about leaving critical batteries connected to the switches for long durations.

All that said, we found magnetic switches to be *extremely* handy in specific situations, such as powering up the science payload. In this case, the payload gave us quick positive feedback that it was enabled, the magnetic switch was located away from other switches so it wasn't likely to be confused, and the payload was not a danger when enabled, so it didn't necessitate any handling protocols. Also, the use of a magnetic switch freed the design of the payload from the design of the airframe, as it didn't require any airframe holes. That meant that we could move the payload between the airframes at will, or completely reconfigure it without drilling new holes.

Tracking

The GPS and APRS tracking system we used in the 70-cm band performed beyond our expectations. We think the u-blox 6 chipset is key to this performance. Improvements in output power, combined with high-gain, circularly-polarized antennas on the ground, gave us an unprecedented real-time understanding of the flight path, out to about 30 miles line-of-sight, and we believe it could go much further. Also, quick-turn firmware changes by the developer got us past some early challenges.

We would like to find a way to get positive feedback when a unit is active and searching for lock, and a better understanding of how far along it is in the lock process. There were many tense moments at the pad, waiting for units to lock without knowing for sure whether they were even powered up. The most critical lesson here is that controlling a beeper-less unit through a magnetic switch is just a bad idea.

Cameras and Shelf Life (Or, How to Avoid Go Fever)

The lesson of the GoPro cameras is really a lesson in parasitic current. Our bench tests had shown that the critical avionics could last days or even weeks with the batteries connected to the magnetic switches. Similarly, we had planned to use the GoPro WiFi Bacpac to power up and activate the cameras, but we found that the Bacpacs themselves would begin to drain the camera's main battery after just a few hours. That meant that a prepared rocket had a "shelf life" of about 6 hours, and if we didn't fly it, we had to completely dismantle it to swap GoPro batteries. This factor alone is enough to give any team "Go Fever."

In the future, we will avoid at all costs any system that limits the shelf life of a prepared rocket to less than a few *days*. Further, we'll look for ways to allow ready access to specific components, like the science payload, while avoiding the dismantling of a packed recovery bay. As noted in the Avionics Bay Design lessons, umbilicals may provide an answer here.

We ultimately determined that the right answer for the GoPro cameras was to omit the WiFi Bacpacs entirely (or replace them with Battery Bacpacs) and just drill a hole to push the power button. Sometimes, the simplest way is the best way.

Airframe Design

After the 104k' flight, we observed that the shock wave on the sustainer reached the airframe about halfway down the body, meaning that we had substantially reduced drag and aerodynamic heating on much of the airframe just by our choice of nose cone.

We saw no aerodynamic heating effects on either sustainer or booster fins, so we think our choice of carbon fiber lamination is fine up to Mach 3.0.

Recovery Systems

On the first full flight, we found that the black powder in the sustainer's apogee CD3 unit had not burned completely and the CO_2 cartridge had not been pierced. The partial burning is typical of black powder at high altitude/low pressure, so it suggests a pressure leak in the powder well. The two possible culprits are the o-rings and the potting of the e-matches. Perhaps we can identify a way to pressure-check a potted cylinder.

On the second full flight, we believe the considerable compression needed to pack the sustainer recovery bay contributed to the failure, wherein the nose cone separated prematurely, at or shortly after booster burnout. We suspect one of the shear pins may have broken in the process of installing it, and the pressure of the recovery gear on the nose cone shoulder coupled with the negative acceleration at booster burnout caused the premature separation. Future iterations of the sustainer should increase the volume of the recovery chamber to allow easier packing of the sustainer. More and/or thicker shear pins would also help.

On the third full flight, we learned how the jet stream can adversely affect deployment. Prior to this, we had only considered how the jet stream might affect the verticality of the flight, or how far a rocket might drift during recovery. On future iterations, we will examine ways to zipper-proof the design without adding airframe breaks that would weaken the structure. We will also look at other ways to control the deployment of the main parachutes, examine the necessity and sizing of the drogue parachutes, and consider ways to better organize shock cords for smooth, gradual deployments. This was the second instance where the nose cone shock cord broke, and both times, it did so right at the knot. Going forward, we will try to stick to sewn loops wherever possible.

Interstage Coupler

In our August test flight of the full stack, we discovered that the thermal expansion of the Delrin coupler presented a problem. The coupler expanded approximately 0.008", which was enough to lock the ISC into the booster when exposed to the high heat of the playa in August.

Other than the expansion issue, which would have been experienced with aluminum anyway, the Delrin functioned perfectly. In future iterations, we may adjust the design to make it less sensitive to temperature swings.

We found our staging system to be very successful. All staging events were straight. The piston ensured stage separation on every flight, and we've learned the importance of proper venting. Although we attribute one sustainer ignition failure to the piston, we believe that is best remedied with better packing or an improved ignition system. We will stick to similar active-separation designs going forward.

Motor Ignition

Although the aft-end ignition system worked on three out of four flights, it did cause grief on every attempt, and forced the recycling of the second full flight. (The resulting rushed preparation contributed to that flight's failure.) The copper tape is fragile and subject to breakage at hard edges. One small tear can require that the entire airframe be repacked. It also requires in-field soldering to connect. And, as seen on the third full flight, the staging mechanism can interfere with aft-end ignition.

We believe it may be possible to develop a head-end ignition system that could be certified for use on sustainer motors. We will pursue this idea further.

Launch System

The conformal rail guides were attached per the instructions, but failed. We might consider using them again if we can find a more secure way to attach them. Rail buttons, on the other hand, are simple and reliable. Our field installation method put an undesirable dependency on the exact placement of the av-bay and tightness of the motor retention and closure, and they are more difficult to install in sections that overlap with the motor. But ideally, a mid-motor button would provide additional guidance, so we need to do more investigation here.

We also determined that we should have been launching from a longer rail. The AeroPac club provided a 14-foot rail, but we will incorporate a larger rail into future plans.

6.0 Assessment and Conclusions

We were thrilled to have reached 104k' on our very first mission attempt!

David Raimondi, Jim Green, Becky Green, Casey Barker, Erik Ebert & Pumpkin, Ken Biba
(Tom Rouse and Steve Wigfield not shown)
Photo: Melanie Barker

Looking back, we are astonished by the measure of success of the program as evaluated by our mission goals.

Goal	Status	Discussion
Achieve 100k'+ AGL per Carmack rules	Yes	Our first mission flight achieved 104k' AGL, even though the flight was off-vertical. We will improve this on future flights.
Efficient airframe	Yes	We believe this airframe is capable of reaching 120-130k' on 21k N*s with a fully vertical launch.
Commercial construction	Yes	Fully certified flight on commercial motors. Only the Interstage coupler requires custom machining.
Reusable flight profile	Yes	Four total flights made on Airframe A, two of which were full 100k' attempts.

Carry science payload	Yes	We flew a 1.5 lb payload consisting of Nexus smartphone with a 5W 2m APRS telemetry system, approximately classic CanSat in volume.
Live webcast of video and telemetry	Yes	We webcast all three mission flights on uStream on the AeroPac web site. We webcast real time telemetry of the sustainer and booster via APRS.
Documentation	Yes	We hope this document will help others pursuing the goal of high altitude flight.

Below, we repeat the table from the original system design benchmarks, this time including the results from Flight 1:

Project	Altitude (m)	Total Impulse (N*s)	Ratio
ARCAS	60960	40000	1.5
GoFast	116000	480000	0.2
FourCarbYen	32004	34150	0.9
Qu8k	36880	143000	0.3
AeroPac 2012	**31900**	**21650**	**1.5**

This table puts our 104k' flight in perspective: It came remarkably close to the ARCAS efficiency benchmark, and without the benefit of a gun launch! With planned improvements, we believe this system can demonstrate an efficiency metric on the order of 1.6-1.7, just by improving the verticality of the flight.

In summary, Flight 1 met our altitude goal and demonstrated that the system works. But for a shear pin and a severed igniter wire, we think Flights 2 and 3 would have gone *even higher*. Every flight we made was recovered safely. We believe we've made great strides towards accessible, reliable, repeatable 100k' flights by amateurs.

7.0 Next Steps

We learned an astonishing amount by doing this project. We learned that we can go very high, while carrying a useful payload, on far less airframe and far less total impulse than was the conventional wisdom in the rocketry hobby. How can we make use of that acquired knowledge?

We are thinking of two ways.

The first is to complete the existing system and improve its reliability and recyclability so that it is a reliable, modest-cost vehicle for putting CanSat payloads into near-space. Since many of us are also ARLISS fliers, we can imagine a new contest for university students: the recovery of an autonomous CanSat robot deployed at 120k' AGL. We believe we have the delivery system for this new class of engineering challenge–ARLISS Extreme.

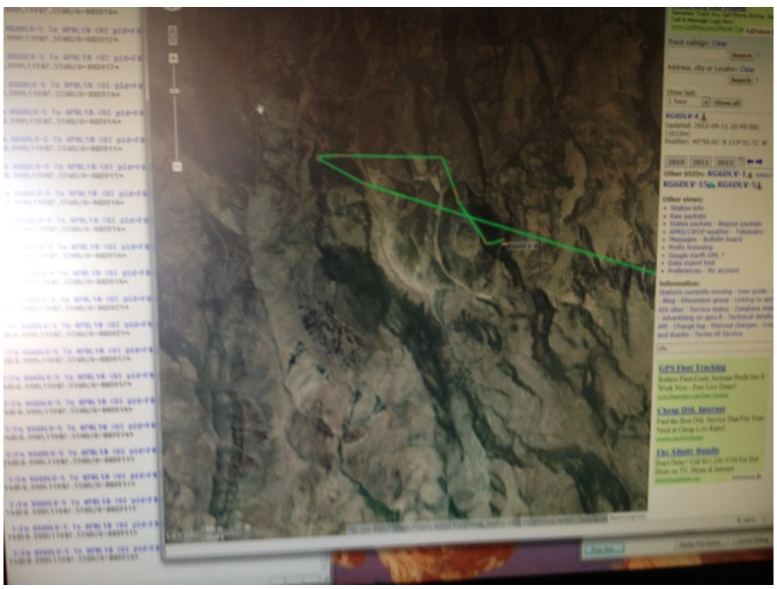
Second, the team believes that getting *much* higher takes a whole lot less N*s of propellant than conventional wisdom suggests.

We are already starting to put the lessons learned into practice. The adventure is just beginning!

Appendix: The Untold Flight 1 Recovery Tale

The VC’s complete coverage of the flight’s GPS telemetry was the key to finding the sustainer. The off-vertical launch exacerbated natural gravity turning, and while going 104k’ high, the sustainer landed 22 miles west of the launch site in very rugged territory.

The final set of GPS coordinates received at the VC were only 500’ above ground level, and we could see that the last portions of the descent were quite vertical. We believed that we knew very precisely (within 100 m) where the sustainer was. The picture below is from the VC computer, showing the APRS track of the flight overlaid on Google Maps by aprs.fi. The green line is the real-time flight track of the sustainer, with the red dots being specific APRS telemetry packets received every 5 seconds from the BeelineGPS in the sustainer.



We could see from the map that it was mountainous country, but there were “roads” on the Google Earth satellite maps.

All we had to do was find it. If we did not have the GPS coordinates, we might never have *attempted* to find it. But because we did have those coordinates *and* we had mapping information suggesting a path to get there, we felt confident that we could get it back.

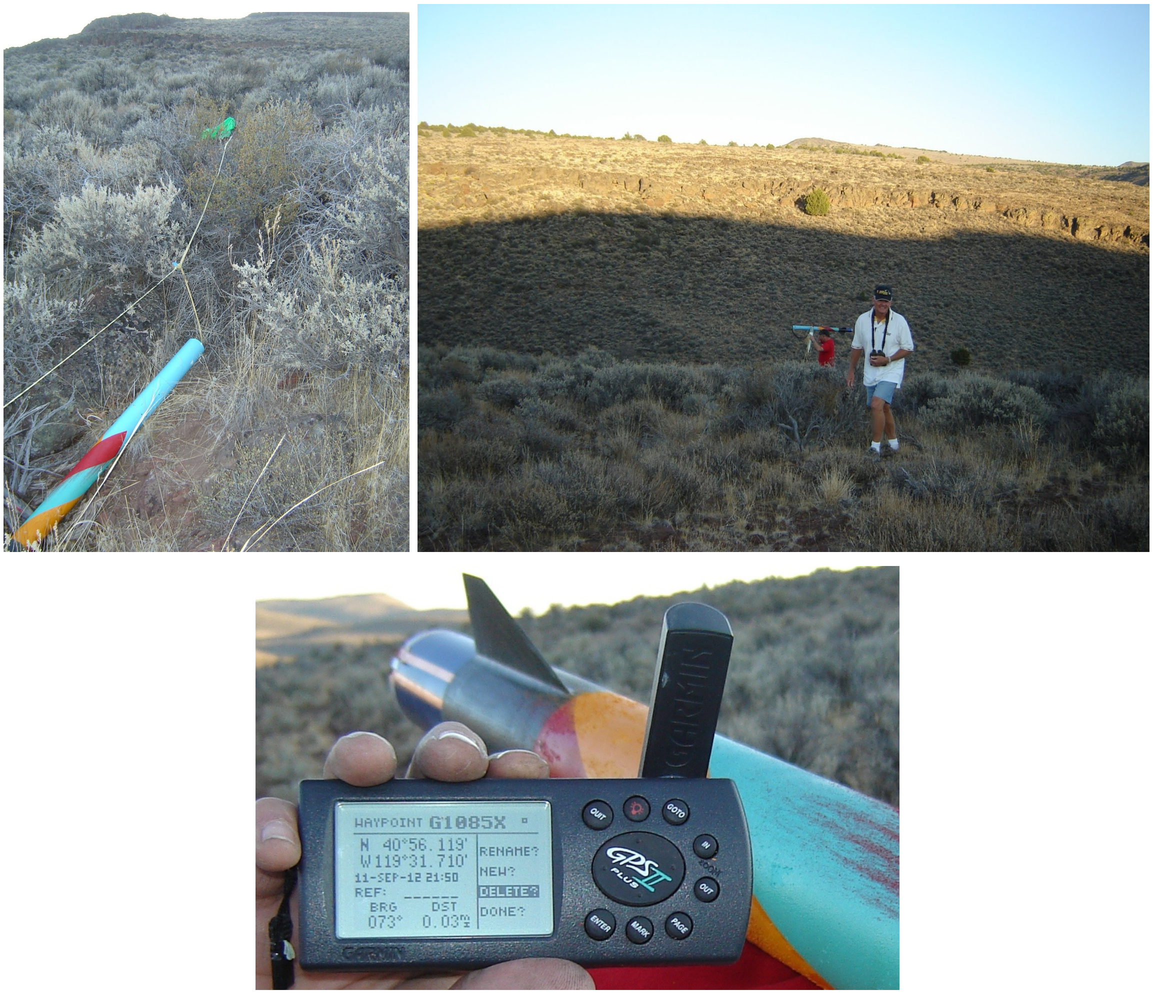
There was a real sense of urgency to go and recover the rocket. The recovery team consisted of Karl Baumann, Ken Biba, and David Raimondi. Ken brought his ham radio and a GPS unit, and David also had his GPS unit. Karl offered his help, so we piled in the AeroTech 4WD truck and set off around 2:30 pm.

When we got close to Squaw Valley Reservoir on RT 447, we started to pay attention for dirt roads heading north from 447. We found the road we wanted to use, but the sign on the locked gate said no trespassing. If this road had been open, we would have been able to quickly get the sustainer, just 11 miles up the valley before us, and a few miles to the east. The next road on 447 was not marked, so we dived in. A couple miles up, the so-called road turned into a dead end. We went back to 447 and headed northwest again.

About this time, two things happened. Ken found another promising dirt road on his GPS unit that was heading east into the mountains, and the batteries died in the ham radio. The loss of the ham radio meant that we could not use it to help find the rocket once we got close, and we couldn't call for help if needed. The next access road was about 7 miles away. By the time we found the dirt road, we were 29 miles straight-line distance from the launch site. This dirt road actually has a name, Lone Juniper Canyon Rd. The road looks great on Google Earth! In reality, the road was great for the first quarter mile or so. We then encountered volcanic rocks, varying from baseball to football in size, with a few larger rocks thrown in for good measure. This would carry on for about 40 yards, and then dirt road again, followed by another field of volcanic rock. Karl has a lot of experience with roads like this and he made the driving look easy while we all bounced up and down in the seats.

Ken kept checking his GPS unit for the next possible road that might take us to the rocket. David kept calling out the current GPS track, bearing, and distance to the rocket, which was slowly getting closer. We turned onto four different roads/trails, and with each turn the excitement built as we slowly got closer to the rocket. Once we reached the road closest to the rocket, the distance rapidly dropped down to 0.1 miles. We told Karl to stop the truck and headed for a gully to the east. Karl wasted no time in getting to a rock outcrop and was looking around when he asked what color the shock cord was, then a moment later, what color the parachute was. Karl had spotted the rocket.

After taking a few pictures and marking the GPS location, we hiked back to the road, about 150 yards away. By this time, the sun was starting to get low in the sky.



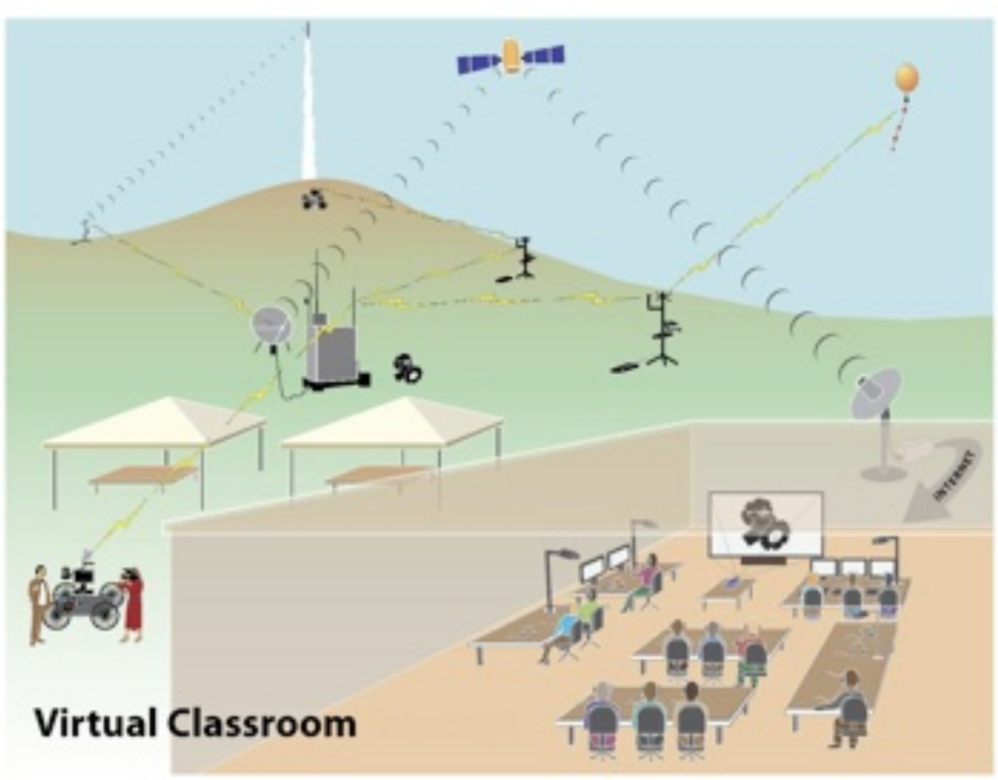
Clockwise from upper left: Sustainer and main chute. Walking back to the "road" with Karl Baumann in the foreground and David Raimondi carrying the sustainer. GPS coordinates for sustainer landing location. Photos: Ken Biba

By the time we retraced our path over the same volcanic rock roads back to HWY 447, it was twilight. Back on the playa, we could see the welcome home beacon 10 miles away. The crew didn't know we were inbound, but Jim Green had a fire going. He tossed in the occasional motor grain scrap, which would flare up into a guiding light. Total recovery time was about 7 hours, and just over 100 miles round trip. It was worth every second of it. We had the sustainer and it was time to celebrate.

Just a quick side note: We all had years of outdoors experience. You would think that we would have been prepared for anything. We didn't take any water, food, or jackets, and we left camp with just over a quarter tank of gas. We all got caught up in the excitement of the moment!

The **100k** team cannot thank Karl enough for his efforts with this project and his help to recover the sustainer. Thank you Karl!

Appendix: Virtual Classroom



The ***Virtual Classroom*** is an integrated wireless network system to provide a distributed, near real-time electronic collaborative environment that allows video, audio, data and sensor participation by a worldwide community in experiments undertaken in physically remote locations. These locations, due to cost, accessibility, safety or other concerns often do not permit communities to participate at the location. For example, all of the student members of a robotic satellite team may not be able to be at the launch and recovery site. The ***Virtual Classroom*** permits all members of these teams with a broadband Internet connection to view and participate in these experiments with many of the tools that on-site experimenters have and might well bring access to remote analysis tools that are impractical to bring to the remote site.

Virtual Classroom Capabilities

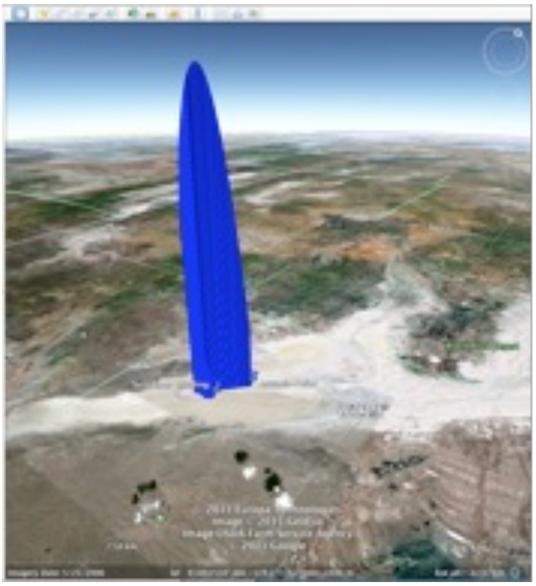
- *Mobile platform based on TV news van with up to 3.5 Kw of mobile power and internal rack mounted electronics bays*
- *40-foot hydraulic mast for antennas and cameras*
- *Data, VoIP, telemetry, video Internet gateway*
- *Dual Internet backbone connections: satellite Internet from a high gain, auto-pointing 1.2-m parabolic dish and 4G mobile cellular*
- *Dual rack mount servers with solid state memory for mobile telemetry and real-time video streaming*
- *WiFi local area communications at 2.4 and 5 GHz of up to 200 Mb/s up to 1000 km^2.*
- *70-cm and 2-m APRS and 30-cm spread spectrum telemetry to balloons, rockets and packet satellites*
- *Amateur 2-m/70-cm and GMRS voice radio*
- *Multiple WiFi remote HD video network cameras for real-time streaming video and audio of events*
- *Standard web browser user interface to video streaming, social media and real-time telemetry*

ARLISS

The ***Virtual Classroom*** is used for the ***ARLISS*** student satellite program at Black Rock, Nevada. ARLISS has a fourteen year history of delivering about 500 autonomous robotic student satellite payloads to about 12,000’ AGL altitude for recovery in harsh desert conditions. The ***Virtual Classroom*** provides real-time video, audio, chat and telemetry support for both payloads and airframes.

Amateur and Sub-Orbital Rocket Flights

The Virtual Classroom is a mobile ground station for high altitude rocket flights for tracking, recovery and overall launch support including video stream of the event.



Near Space Balloon Flights

2-meter APRS services have often been used to track and support high altitude near earth balloon experiments. The ***Virtual Classroom*** supports these legacy services but adds high bandwidth IEEE 802.11 services that can extend to the altitudes these balloons achieve. The ***Virtual Classroom*** provides real-time forwarding of these experiments to the Internet and real-time access from remote experimenters to these experiments.

Robot Tele-Presence

Robots can benefit from high bandwidth, multimegabit communications. High bandwidth communications permit near real-time remote processing of data rich media. The ***Virtual Classroom*** is expected to be a strong asset for such robotic experiments.

New Applications

Originally designed for support of student satellite experiments, the ***Virtual Classroom*** can be easily extended to provide remote access to any field based experiments. One intriguing future new application is the exploration of extending IEEE 802.11 communications to domains currently unexplored. Overhead high bandwidth network coverage to near space - high altitude rockets, balloons and LEO satellites – is a potentially profitable area of examination.

Open System

The ***Virtual Classroom*** is an inexpensive, open system platform constructed with the intent of ease of replication for other experimenters and applications.